FERMI GAMMA-RAY SPACE TELESCOPE (*Fermi*)

CICERONE:

Detailed Manual for the *Fermi* Science Tools

February 6, 2009

GODDARD SPACE FLIGHT CENTER

FERMI GAMMA-RAY SPACE TELESCOPE
(*Fermi*)

CICERONE

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NASA Goddard Space Flight Center

Greenbelt, Maryland

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FERMI SCIENCE TOOLS CICERONE

The documentation for the *Fermi* Science Tools consists of four components:

- A software installation guide.
- A series of analysis threads that walk the user through some standard analyses.
- A reference manual that provides a succinct description all the parameters for each tool. This manual will be useful for experienced users.
- The purpose of this manual, or 'cicerone,' is to provide greater insight into the use of the tools and the data analysis techniques behind them. The Cicerone is also available in one printable PDF document.

Cicerone means 'a person who conducts sightseers; guide', and was apparently first applied to learned antiquarians who would show people around the ancient monuments of Italy.

The word is taken from the name of Cicero (full name, Marcus Tullius Cicero; sometimes he is called "Tully"), the Roman orator and statesman. The reference is that the guide is thought of as having the eloquence or learning of Cicero...

The word cicerone is taken from Italian, which in turn borrows from Latin; the -n- comes from Ciceron-, the Latin stem of Cicero. It is first found in English in the early eighteenth century.

—From the Random House Mavens' Word of the Day.

The GLAST Science Tool Cicerone consists of the following sections:

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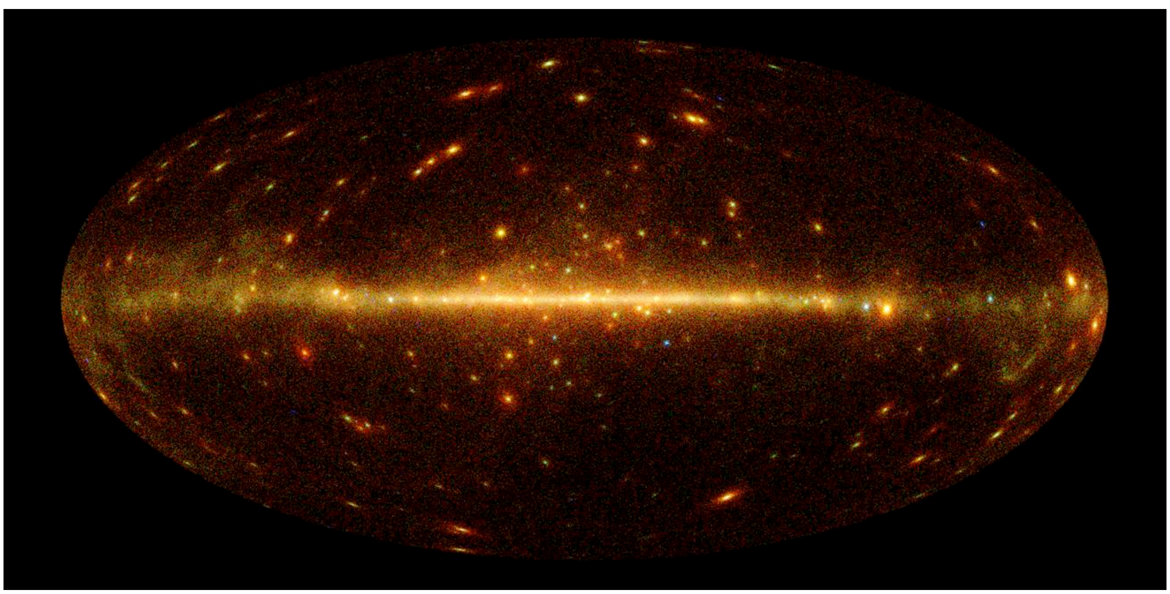
1 INTRODUCTION

1.1 Overview of the Cicerone

This cicerone is written to make you an informed user of the *Fermi* Gamma-ray Space Telescope (FGST) Science Tools, the tools that will enable you to derive astrophysical information from the lists of photons detected by *Fermi* 's two instruments, the Large Area Telescope (LAT) and the *Fermi* Gamma-ray Burst Monitor (GBM). The data you will analyze are in some aspects simpler and in other aspects more complicated than the data provided by X-ray missions such as RXTE or Chandra. The *Fermi* detectors operate in few different modes and thus do not produce a multitude of data products that have to be handled differently. On the other hand, proper analysis of the LAT data for most sources requires a new model-fitting tool based on a maximum-likelihood method that may be unfamiliar and whose misuse might lead to spurious results. Therefore, this document spends relatively less space on data and more space on analysis software than similar manuals (often called 'ABC Guides') for other missions. This manual includes a description of the instruments and the mission operations as a foundation for understanding the analysis tools.



Simulated gamma-ray sky as observed by the LAT after 55 days (graphic by Seth Digel)

The *Fermi* data will be analyzed by members of both the general scientific community and the instrument teams, and by both high energy astrophysicists and particle physicists. The text is written for the general scientific community. Because this is a broad audience, this document may seem elementary in places for some, and use unfamiliar terminology for others. We hope that our explanations of concepts are sufficiently clear for the neophyte, yet detailed enough to be useful for the advanced user.

We must arbitrarily choose among divergent practices to establish some fundamental terms. In our usage a 'photon' is the electromagnetic quantum that is incident on a detector, regardless of the properties of that detector. Therefore, a photon spectrum is the flux of photons that arrives at the detector, and is unaffected by the detector's response. An 'event' is the result of the response of the detector to a photon or charged particle, or noise that mimics a particle. A 'count' is an event that is considered to have resulted from an incident photon, and therefore depends on the response of the detector and vagaries of the detection process. We distinguish between a 'count' and a 'photon' because not all photons incident on the detector will result in counts (some photons will be undetected or will be rejected as background), and not all counts result from photons (some counts are produced by non-astrophysical background). In addition, a photon is characterized by true values of properties such as energy and direction, while counts will be characterized by detector-modified observables.

We invite users to comment upon this document through the *Fermi* Science Support Center Helpdesk at http://fermi.gsfc.nasa.gov/ssc/help/.

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1.2 Overview of the Mission

Fermi will perform gamma-ray measurements over the entire celestial sphere, with a sensitivity factor of 30 or more greater than obtained by earlier gamma-ray missions. *Fermi* has accomplished the next major advance in high-energy gamma-ray astrophysics by providing significant improvements in angular resolution, effective area, field-of-view (FOV), energy resolution and range, and time resolution.

Fermi observatory being prepared for launch

Fermi's scientific objectives are satisfied by two instruments. Covering the 20 MeV to >300 GeV energy range, the Large Area Telescope (LAT) has a large collecting area, an imaging capability over a large FOV, and the time resolution and low deadtime sufficient to study transient phenomena. The LAT also provides active background discrimination and rejection against the large fluxes of cosmic rays, earth albedo gamma rays, and trapped radiation that are encountered in orbit. The *Fermi* Gamma-ray Burst Monitor (GBM) provides the spectral and temporal context in the classical 10 keV to 25 MeV energy band for gamma-ray bursts (GRBs) observed by the LAT, detects and localizes bursts, and alerts the LAT that a burst is in progress. *Fermi* can autonomously alter its observing plan to observe strong GRBs during and after the low-energy gamma-ray emission, and provides rapid notification to the science community. The next sections describe the instruments in greater detail.

The primary communication between the spacecraft and the ground is through the Tracking and Data Relay Satellite System (TDRSS). Science and housekeeping data are downlinked at Ku-band frequencies ~10-11 times per day at 40 Mbps during seven to eight minute real time telemetry contacts. During these downlinks there is a direct 4 kbps uplink rate available at S-band frequencies. Burst alerts and spacecraft alarms can be downlinked in the S-band (variable data rates) at all times. S-band uplink and downlink (no science data) directly to ground stations is possible as a backup to TDRSS. Time and spacecraft position are provided by an onboard GPS system.

1.2.1 Mission Timeline

Fermi was launched in June 11, 2008, from Cape Canaveral by a Delta 2920H-10 (also known as a Delta II 'Heavy') into an initial orbit of ~565 km altitude at an 25.6 degree inclination with an eccentricity <0.01. The orbital period is 96.5 minutes, and has a precession period of 53.4 days (so the RA and Dec of the orbit poles trace a 25.6 degree circle on the sky every 53.4 days). The mission design lifetime is a minimum of 5 years, with a goal of 10 years.

After launch the mission consists of three phases: a ~2 month on-orbit initial checkout (Phase 0), a one year science verification period during which a full sky survey will be performed (Phase 1), and then at least four years of operations determined by the scientific goals and requirements of guest investigations (Phase 2). There is one cycle of guest investigations during the verification and sky survey phase, and annual guest investigation cycles during Phase 2. The GBM data will be publicly released during Phase 1 while the LAT data to which the tools described here can be applied will be released only in Phase 2, i.e., about 14 months after *Fermi's* launch.

1.2.2 Observing Modes

The LAT and GBM have very wide FOVs, and the observatory is very flexible in the direction in which it can point. An observational constraint is to avoid pointing at or near the Earth to maximize the detection of astrophysical photons. However, the LAT may occasionally observe the Earth's limb to detect albedo gamma rays for instrument calibration. Orientation requirements for the LAT's cooling radiators, the battery radiators, and the observatory solar panels also impose engineering constraints, particularly during slewing maneuvers. No science data is taken while the observatory is transiting the South Atlantic Anomaly (SAA) since the instruments lower the voltage on their photomultiplier tubes (PMTs). The SAA is a region over the South Atlantic with a high density of charged particles that are trapped by the configuration of the Earth's magnetic field. In a 25.6 degree inclination orbit and at *Fermi*'s altitude, SAA outages cost ~15% of the LAT's and GBM's potential observing time.

The *Fermi* spacecraft operates in a number of observing modes. Transitions between modes may be commanded from the ground or by the spacecraft. Based on data from the LAT or the GBM, the LAT can request autonomous repointing of the spacecraft and change the observing mode to monitor the location of a GRB (or other short timescale transient) in or near the LAT's FOV. After a pre-determined time the spacecraft will return to the scheduled mode. Currently the dwell time for such autonomous repoints is five hours. The pointing accuracy is <2 degrees (1 σ, goal of <0.5 degrees), with a pointing knowledge of <10 arcsec (goal <5 arcsec).

In survey mode, which will probably predominate during most of the mission (e.g., >80% of the observing time), the LAT's pointing is relative to the zenith (the direction away from the Earth), and therefore changes constantly relative to the sky. Uniformity of exposure is achieved by "rocking" the pointing perpendicular to the orbital motion. The default profile rocks the instrument axis 35 degrees north for one orbit, then 35 degrees south for one orbit, resulting in a two-orbit periodicity. The maximum rocking angle is 60 degrees. The figure-of-merit to be optimized by a particular rocking profile is nominally uniformity of sky coverage, but may change as the mission progresses.

When justified by the demands of a particular investigation, the LAT can be pointed at (or near) a target. A pointed observation may be optimum for pulsar timing studies (to reduce the effect of variations in a pulsar's period) or for other studies where building up exposure over a short time will be useful. This mode keeps the earth out of the FOV; the default Earth Avoidance Angle (defined as the minimum angle between the LAT axis and the Earth's limb) is 30 degrees. When the target is unocculted but within the Earth Avoidance Angle of the Earth's limb, the spacecraft will keep the target in the LAT's FOV while keeping the Earth out of the LAT's FOV. The observatory may observe a secondary target when the Earth occults the primary target.

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1.3 Overview of the LAT

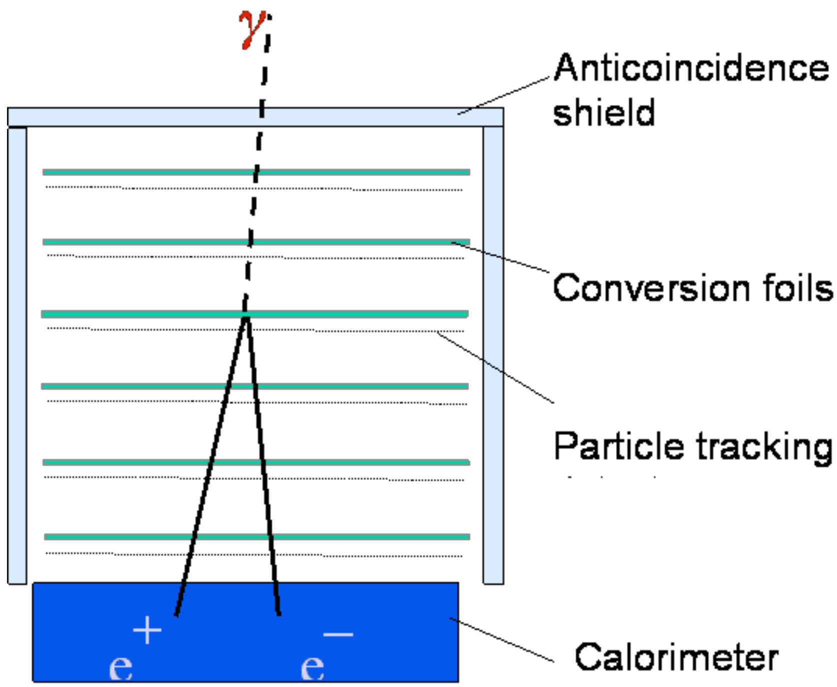
The LAT's principal objective is high sensitivity gamma-ray observations of celestial sources in the energy range from ~20 MeV to >300 GeV. As the table below demonstrates, the LAT will have a wide FOV, large effective area, good energy resolution and good angular resolution. The LAT will detect point sources that are more than 200 times fainter than the Crab nebula. For strong point sources, the position will be determined to about 0.5 arcminute. Spectra will be measurable over the entire energy range for the stronger sources.

1.3.1 Instrument Capabilities

Characteristic	**Capability**
Energy Range	<20 MeV to >300 GeV
Energy Resolution	<10% on axis, 100 MeV-10 GeV
Effective Area	>8,000 cm^2 maximum effective area at normal incidence; includes inefficiencies to achieve required background rejection
Single Photon Angular Resolution	<0.15º, on-axis, 68% space angle containment radius for E>10 GeV; <3.5º, on-axis, 68% space angle containment radius for E=100 MeV
Field of View	>2 sr
Source Location Determination	<0.5 arcmin for high-latitude source
Point Source Sensitivity	$<6\times10^{-9}$ ph cm^{-2} s^{-1} for E>100 MeV, 5σ detection after 1 year sky survey
Time Accuracy	<10 microseconds, relative to spacecraft time
Background Rejection (after analysis)	<10% residual contamination of high latitude diffuse sample in any decade of energy for E > 100 MeV.
Dead Time	<100 microseconds per event

1.3.2 Detector Methodology

The LAT is a 'pair conversion' detector. Gamma rays penetrate into the detector and interact with a high Z converter material, in this case tungsten, to produce an electron-positron pair. Since the gamma-ray energy is much larger than the rest mass of the electron and positron, both members of the pair continue predominantly in the direction of the incident gamma ray. The passage of the electron and positron through the detector is tracked by components that are sensitive to the passage of charged particles, in this case of the LAT silicon strip detectors. At the bottom of the detector is a calorimeter made of CsI(Tl) that is thick enough to stop the electron-positron pair, in the process recording the total energy deposited, and tracking the pair before the particles stop.



Schematic Structure of the LAT

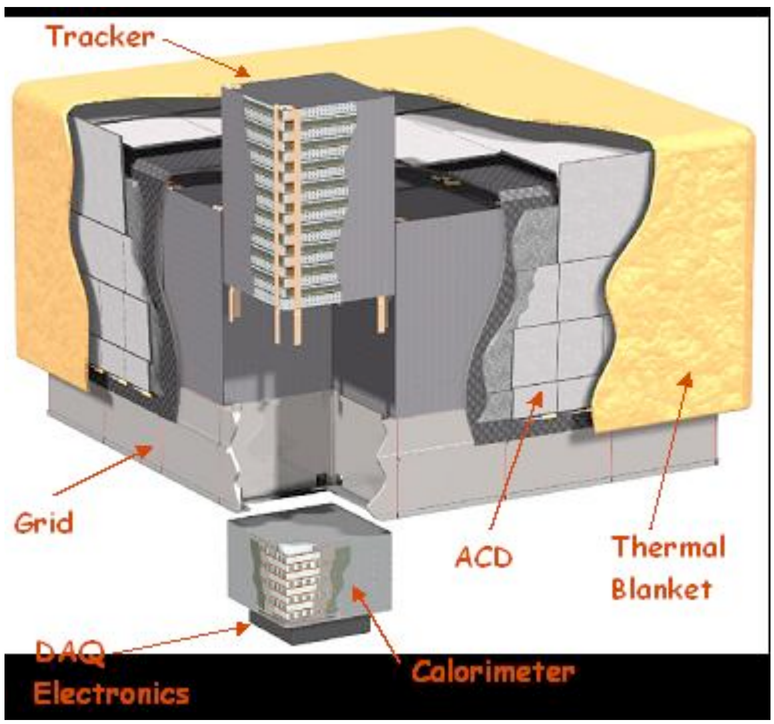
Charged particles incident on the LAT also pair produce in the LAT, resulting in multiple charged particle tracks. To veto these charged particles, which are noise for an astrophysical telescope, the LAT is surrounded by an anticoincidence detector (ACD), tiles that scintillate when traversed by a charged particle. Sometimes a very high energy gamma ray produces a charged particle that exits the LAT through the ACD; the EGRET detector on CGRO had a monolithic ACD that vetoed many high energy gamma rays. Therefore the LAT ACD is segmented, and only events that trigger an ACD tile on the path of the incoming particle are vetoed. The segmentation also results in a more uniform threshold over the ACD. This segmentation of the LAT ACD increases the LAT's sensitivity to high-energy gamma rays dramatically relative to EGRET.

The output from the LAT consists of the pulse-height signals produced as charged particles deposit energy in different parts of the tracker and calorimeter. By combining the pulse heights with the x-y coordinates of each silicon strip detector hit one can reconstruct the particle trajectory and energy losses. The analysis both onboard and on the ground reconstructs the tracks of the charged particles from these data, and then characterizes the interaction that produced the charged particles; this analysis can distinguish between events resulting from photons and background, determine the incident direction and estimate the energy.

1.3.3 Detector Structure

The LAT consists of an array of 16 tracker (TKR) modules, 16 calorimeter (CAL) modules, and a segmented ACD. The TKR and CAL modules are mounted to the instrument grid structure.

Each TKR module consists of 18 XY tracker planes. Each XY plane has an array of silicon-strip tracking detectors (SSDs) for charged particle detection. The first 12 planes have 0.035 radiation length thick tungsten plates in front of the SSDs, the next 4 planes have 0.18 radiation length thick tungsten plates, and the last 2 planes, immediately in front of the CAL, do not have tungsten plates. A radiation length is defined as the length in a specific material in which an energetic electron will lose $1-e^{-1}$ of its energy by bremsstrahlung. The SSDs in each plane actually consist of two planes of silicon strips, one running in the x and the other in the y direction, thereby localizing the passage of a charged particle. Gamma rays incident from within the LAT's FOV preferentially convert into an electron-positron pair in one of the TKR's tungsten plates. The initial directions of the electron and positron are determined from their tracks recorded by the SSD planes following the conversion point. Bremsstrahlung in the first conversion plane results in an angular deflection that results in a fundamental limit to the low energy angular resolution. Cosmic rays also interact within the TKR modules. Reconstruction of the interactions from the tracks identify the type of particle as well as its energy and incident direction.



Structure of the LAT

Each CAL module consists of 8 planes of 12 CsI(Tl) crystals each. The crystals are read out by PIN diodes at each end. The CAL's segmentation and read-out provide precise three-dimensional localization of the particle shower in the CAL. At normal incidence the CAL's depth is 8.5 radiation lengths. The CAL is a total absorption (not sampling) calorimeter with excellent energy resolution.

The ACD is composed of plastic scintillator segmented into tiles, supplemented with fiber ribbons, and read out by waveshifting fibers connected to PMTs.

The LAT's Data Acquisition System (DAQ) performs preliminary cuts on events within the LAT, to reduce the rate of background events that will be telemetered to the ground. The DAQ processes the captured event data into a data stream with an average bit rate of 1.2 Mbps for the LAT. The DAQ will also perform: command, control, and instrument monitoring; housekeeping; and power switching. Onboard processing can be modified by uploading new software, if necessary.

The astrophysical photons of primary interest will be a tiny fraction of the particles that will penetrate into the LAT's TKR. The LAT will perform on-board analysis cuts that will reduce the ~2.5 kHz event rate that trigger the TKR to ~400 Hz event rate that will be sent to the ground for further analysis; of these ~400 Hz only ~2-5 Hz are astrophysical photons. The data for an event that passes the on-board analysis cuts is stored in a packet with a time stamp and details of the signals from the various LAT components. Because the number of signals for a given event varies, the data packets have variable length. These data packets describing each event are the LAT's primary data product. The LAT transfers these packets to the spacecraft's solid state recorder (SSR) for subsequent transmission to the ground.

1.3.4 The LAT Collaboration

The *Fermi* LAT collaboration includes scientists from Stanford University, including SLAC (PI: Prof. P. Michelson); GSFC (Project Scientist: S. Ritz); University of California at Santa Cruz; Naval Research Laboratory; University of Washington; Sonoma State University; Ohio State University; University of Denver; Perdue University – Calumet; and Yahoo Inc. in the United States; Stockholm University and Royal Institute of Technologyin Sweden; Commissariat a l'Energie Atomique, Departement d'Astrophysique, Saclay; Institut National de Physique Nuclearie et de Physique des Particules; and Centre d'Etude Spatiale des Rayonnements in France; Instituto Nazionale di Fisica Nucleare; Agenzia Spaziale Italiana; Instituto di Fisica Cosmica, CNR; and Universita e Politecnico di Bari in Italy; Hiroshima University; Institute of Space and Astronautical Science; and the Tokyo Institute of Technology in Japan; and Institut de Ciencies de l'Espai in Sapin. In addition, 29 institutions world-wide host Affiliated Scientists.

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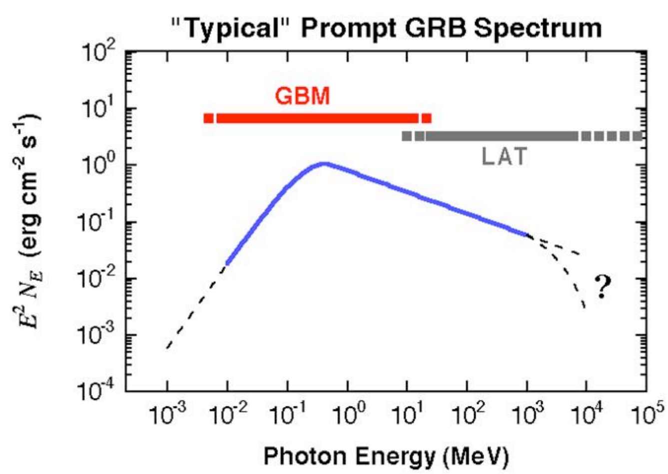
1.4 Overview of the *Fermi* GBM

The *Fermi* GBM provides simultaneous low-energy spectral and temporal measurements for all GRBs within the LAT FOV. The combined GBM and LAT effective energy range spans more than 7 energy decades from 10 keV to 300 GeV. The GBM extends the energy coverage from below the typical GRB spectral break at ~100 keV to above the LAT's low-energy cutoff for inter-instrument calibration. Furthermore, the GBM's sensitivity and FOV are commensurate with the LAT's to ensure that many bursts will have simultaneous low-energy and high-energy measurements with similar statistical significance. The GBM also assists the LAT in detecting and localizing GRBs rapidly by providing prompt notification to the ground of a burst trigger. Finally, the GBM provides coarse GRB locations over a wide FOV that can be used to repoint the LAT at particularly interesting bursts (both inside and outside the LAT FOV) for gamma-ray afterglow observations. These locations are also sent to the ground to notify external follow-up observers.



Gamma-ray burst spectral coverage of the *Fermi* GBM and the LAT

Using detection criteria similar to those of *CGRO*'s Burst And Transient Source Experiment (BATSE), the predicted GBM burst detection rate is ~200 bursts per year.

In addition to measuring low-energy spectra below the LAT threshold, the GBM significantly improves the constraints on high-energy spectral behavior compared to those of the LAT alone. The combination of GBM and LAT data therefore provides a powerful tool to study GRB spectra and their underlying physics.

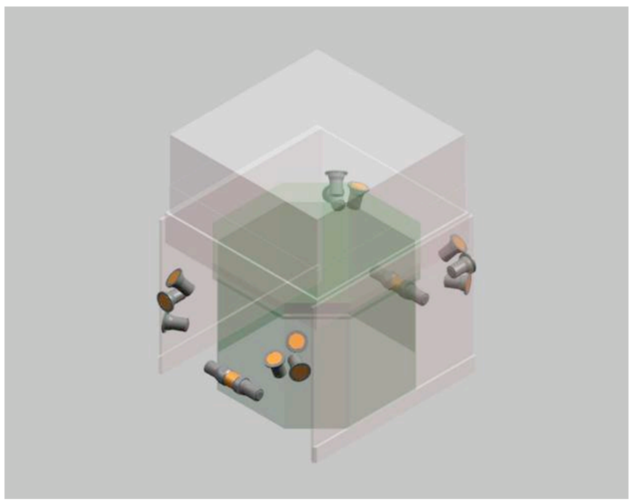
1.4.1 Detector Capability

Characteristic	Capability
Low Energy Limit	<10 keV
High Energy Limit	>25 MeV
Energy Resolution (FWHM, 0.1-1 MeV)	<10%

Field of View (Co-aligned with LAT FOV)	>8 sr
Time Accuracy (Relative to spacecraft time)	<10 microseconds
Average Dead Time	<10 microsecond/count
Burst Sensitivity (Peak 50-300 keV flux for 5σ detection in ph cm^{-2} s^{-1})	<0.5 cm^{-2} s^{-1}
Burst Alert Locations (1σ systematic error radius)	<15º
Burst Alert Time Delay (Time from burst trigger to spacecraft notification (used to notify ground or LAT)	<2 s

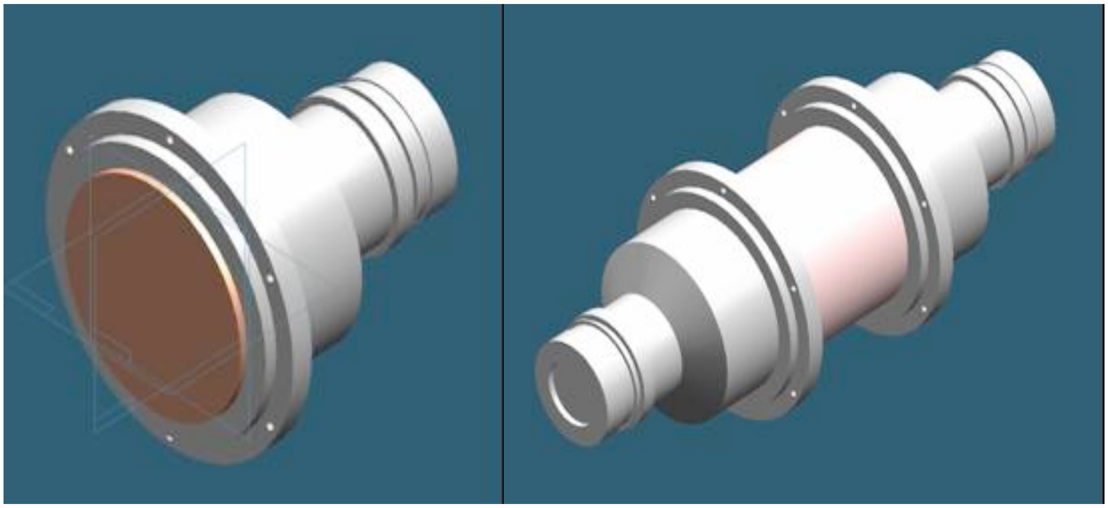
1.4.2 Hardware

To achieve the required GBM performance, the design and technology borrow heavily from previous GRB instruments, particularly from BATSE. Like BATSE, the GBM uses two types of cylindrical crystal scintillation detectors, whose light is read out by PMTs.



Placement of the GBM on *Fermi*

An array of 12 sodium iodide (NaI) detectors (0.5 in. thick, 5 in. diameter) covers the lower end of the energy range up to ~1 MeV. The GBM triggers off of the rates in the NaI detectors. Each NaI detector consists of the crystal, an aluminum housing, a thin beryllium entrance window on one face, and a 5 in. diameter PMT assembly (including a pre-amplifier) on the other. These detectors are distributed around the *Fermi* spacecraft with different orientations to provide the required sensitivity and FOV. The cosine-like angular response of the thin NaI detectors are used to localize burst sources by comparing rates from detectors with different viewing angles. To cover higher energies, the GBM also includes two 5 in. thick, 5 in. diameter bismuth germanate (BGO) detectors. The combination of the BGO detectors' high-density (7.1 g cm^{-3}) and large effective Z (~63) results in good stopping power beyond the low end of the LAT energy range at ~20 MeV. The BGO detectors are placed on opposite sides of the *Fermi* spacecraft to provide high-energy spectral capability over approximately the same FOV as the NaI detectors. For redundancy, each BGO detector has two PMTs located at opposite ends of the crystal.



The *Fermi* GBM's NaI (left) and BGO (right) detectors

The signals from all 14 GBM detectors are collected by a central Data Processing Unit (DPU). This unit digitizes and time-tags the detectors' pulse height signals, packages the resulting data into several different types for transmission to the ground (via the *Fermi* observatory), and performs various data processing tasks such as autonomous burst triggering. In addition, the DPU is the sole means of controlling and monitoring the instrument. For example, the DPU controls the PMTs' power supply to maintain their gain.

1.4.3 Data Types

There are three basic types of GBM science data: (1) continuous data consisting of the count rates from each detector with various (selectable) energy and time integration bins; (2) trigger data containing lists of individually time-tagged pulse heights from selected detectors for periods before and after each on-board trigger; and (3) Alert Telemetry sent down to the ground immediately after a burst containing computed data from a burst trigger, such as intensity, location, and classification. The Burst Alert, the first packet of the Alert Telemetry, arrives at the Gamma-ray burst Coordinates Network (GCN) within 15 seconds of the burst detection. Alerts originating in the GBM are also sent to the LAT to aid in LAT GRB detection and repointing decisions. The remaining data types are transmitted via the scheduled Ku-band contacts. The GBM produces an average of 1.4 Gbits/day, with a minimum of 1.2 Gbits/day and a maximum allocated rate of 2.2 Gbits/day.

1.4.4 The *Fermi* GBM Collaboration

The *Fermi* GBM collaboration includes scientists from the Marshall Space Flight Center (PI: Dr. C. A. Meegan), the Max Planck Institute for Extraterrestrial Physics (MPE; Co-PI: Dr. J. Greiner), the University of Alabama in Huntsville, the Universities Space Research Association (USRA), and Los Alamos National Laboratory. The Marshall, University of Alabama, and USRA scientists are housed at the National Space Science and Technology Center (NSSTC) in Huntsville.

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1.5 Operations

1.5.1 Mission Phases and Cycles

Phase 0 was the on-orbit checkout, which completed on August 4, 2008. The spacecraft subsystems were evaluated and checked first. Subsequently, the instruments were turned on, tested, and calibrated, and the main observation modes were verified. The LAT event data accumulated during this phase is proprietary to the LAT instrument team until the beginning of Phase 2.

Phase 1 began as soon as *Fermi* was declared operational. During this phase *Fermi* carries out a one-year validation and sky survey program. The performance of the science instruments is being fully characterized and validated, and the data processing pipelines are being refined based on operational experience. The spacecraft is operating primarily in a sky survey mode designed for relatively uniform sky coverage. The survey may be interrupted by Target-of-Opportunity (TOO) observations to follow 5-10 bright transients (typically for a few orbits), or by autonomous repointing for GRB followup. The LAT event data accumulated during this phase is also proprietary to the LAT instrument team until the beginning of Phase 2. The LAT team will release spectra and lightcurves for ~23 sources of interest to the community and bright transients. A preliminary Bright Source List was released on February 6, 2009. GBM burst data is released as soon as it is processed.

During Phase 2 the mission timeline will be determined by the selected GI observations proposed in response to NRAs for the *Fermi* GI Program. Because of the LAT's wide FOV, survey mode is anticipated to remain the baseline operational mode during this phase of the *Fermi* mission. The expected frequency, criteria and figures-of-merit for the different observation modes will be announced to the scientific community.

The GI program will go through approximately annual cycles. The first GI cycle coincided with Phase 1, and selected Phase 1 guest investigations were not to interfere with the validation of the instruments or the all-sky survey. During Cycle 1 the scientific community will not have access to LAT event data, but will have access to spectra and lightcurves of selected sources and transients. During subsequent cycles GIs may propose deviations from survey mode, and will have access to all the science data.

Therefore, during the ~14 months after launch the scientific community will **not** analyze LAT event data with the tools described in this Cicerone, but once these data become publicly available, more than a full year's worth of counts will be available for analysis. During Cycle 1, GBM data will be available for analysis using the appropriate tools.

1.5.2 The Ground System

As a member of the general scientific community your primary contact with the *Fermi* mission will be with the *Fermi* Science Support Center (FSSC) at the Goddard Space Flight Center (GSFC). The FSSC provides the scientific community with data, the

Science Tools, and documentation. Members of the FSSC manage the *Fermi* Guest Investigator (GI) program on behalf of NASA HQ. The FSSC also creates the observing timeline based on successful GI observing proposals and the default observing mode.

The data telemetered down from *Fermi* enters the *Fermi* ground system through the Mission Operations Center (MOC), staffed by the Flight Operations Team (FOT) and also housed at GSFC. The MOC 'cleans up' the telemetry, monitors the spacecraft through the housekeeping portion of the telemetry, and transmits the appropriate telemetry to the other ground system elements. The MOC also sends commands to the spacecraft, particularly a weekly load of observing and operational commands.

Each instrument team maintains an Instrument Operations Center. The LAT Instrument Science and Operations Center (LISOC) is located at SLAC in Palo Alto, CA, while the *Fermi* GBM operates the GBM Instrument Operations Center (GIOC) in Huntsville, AL. The Instrument Operations Centers receive the 'cleaned up' telemetry, monitor their detectors through the housekeeping portion of the telemetry, process the science data, and transmit the resulting science data products to the FSSC. The LAT science data processing is quite extensive, starting with event reconstruction from the 'hits' in different parts of the LAT and ending with a characterization of these events. The Instrument Operations Centers also serve data to members of their teams.

This model of the ground system is more decentralized than usual, with the instrument teams taking a more active role in the routine processing of the science data. Data processing occurs at each ground system element, leading to a straightforward set of data 'levels.' The MOC removes corrupted or duplicate telemetry packets, and ensures that the packets are in time order; the resulting 'cleaned up' telemetry is called Level 0 data. The Instrument Operations Centers process the instrument-dependent data, creating event lists; the data that leaves is called Level 1 data. Finally, processing by scientists using the Science Tools results in Level 2 data. As LAT data is released to the public, the FSSC will create and post count and exposure maps on weekly, monthly, and yearly timescales.

Catalogs and compendia of Level 2 data are considered Level 3 products.

1.5.3 Observations

The FOVs of *Fermi's* two detectors are very large and therefore the concept of an 'observation' of a given source is not very meaningful. Useful LAT data can be taken over approximately 30% of the sky at any time (although the effective area will vary over the FOV), and therefore while data are accumulated for a given source, data are also accumulated for a large number of other sources. As described in the mission overview, survey mode will predominate during at least the early part of the mission. In this mode the LAT will alternate pointing 35 degrees (default) above or below the orbital plane; this observing mode provides uniform sky coverage every 2 orbits (~3 hours) with the equivalent of 30 minutes of on axis exposure. Pointed and modified survey observations will be permitted during Phase 2, but must be justified. Even during these deviations from the standard survey mode, counts accumulated from one source will be interspersed with counts from many other sources.

Thus instead of thinking about the LAT data as consisting of a number of independent observations of discrete sources, the LAT data should be conceptualized as a continuous event list from the beginning of the mission to the end with counts from your source appearing with greater or lesser frequency depending on the LAT's effective area towards the source at a given time.

1.5.4 Target of Opportunity Observations and Autonomous Repoints

As a consequence of a transient phenomenon in the sky, the *Fermi* Project Scientist (or his/her designee) can declare a 'target of opportunity' (TOO) observation resulting in a pointed observation. This TOO observation may result from a GI notifying the Project Scientist that the criteria for a TOO observation in a successful GI proposal have been met or a request from the community; these requests for a TOO observation, whether or not previously proposed, will be submitted through a website. In Phase 2 the data accumulated during a TOO observation is not proprietary to the requester; in Phases 0 and 1 the LAT event data are not public.

Similarly, if either the LAT or GBM detect a gamma-ray burst that is sufficiently bright then the spacecraft can autonomously repoint towards the burst location for five hours (the current default).

Note that pointing towards the object of a TOO observation or a burst after an autonomous repoint increases the accumulation of exposure towards the source or burst. Even without the TOO observation or the autonomous repoint the source or burst origin will be monitored if *Fermi* is in survey mode. And during the TOO observation or autonomous repoint useful data will be accumulated from other sources.

1.5.5 Data Latency

Data from the *Fermi* GBM and the LAT are stored in the spacecraft's Solid State Recorder (SSR) as the data are taken; the instruments do not store these data internally. While the system specifications permit 72 hours from the taking of source data until data are available from the FSSC, the actual data latency is typically much less. Although the SSR can hold up to 30 hours of data, the data is downlinked from the spacecraft through a TDRSS satellite 6-7 times per day on the Ku band. Thus in normal operations the data should reside on the spacecraft for only ~3 hours before being downlinked. While the LAT instrument team is permitted up to 24 hours to process the data, the data pipeline is designed to process the data from a given downlink before the data from the next downlink arrives. Similarly, while the FSSC is permitted 24 hours to ingest data and make it available, the FSSC plans to complete processing the data from one data transfer before the next such transfer.

Thus in practice LAT data latency should be ~12 hours.

The GBM team processes their data after every downlink. Burst data is transferred to the FSSC as soon as processing is completed. Daily data products are packaged into one day units. Thus, the burst data should have a shorter latency than routine daily data.

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2 ANALYSIS THREADS

2.1 Use of the Analysis Threads

The analysis threads are meant to demonstrate the use of the science tools for a number of standard types of analyses, and indeed, many users may find working through these threads to be the best introduction to the tools. Some of the threads present elementary analyses and start with the extraction of the data from the relevant databases, while others are more advanced analyses that assume that certain processing has already occurred.

But before you, the new user, attempt to follow these threads you should be acquainted with some basic concepts about the data.

Then you should try the 'Data Selection' threads. 'Extract LAT Data' shows you how to extract the data from the FSSC data server and how to perform additional cuts on the data. 'Explore LAT Data' shows you how to explore the data.

Currently only the threads describing analyses covered by the documentation are included here.

- Extract the LAT Data from the FSSC Data Server
- Explore the LAT Data
- Explore the LAT Data (Bursts)

If you are interested in standard LAT point source analysis, then you should study the 'Source Analysis' threads.

- Likelihood Tutorial
- Binned Likelihood Tutorial
- Identification of LAT Sources

If you are interested in analyzing gamma-ray burst spectra from the LAT or the GBM, then you should study the 'GRB Analysis' threads.

- Analysis of LAT Burst Observations
- Analysis of GBM Burst Observations

If you are interested in analyzing pulsar data, then you should study the 'Pulsar Analysis' threads.

- Pulsar Analysis

- Period Search
- Pulsation Search
- Periodicity Test
- Pulse Phase Calculation
- Binary Orbital Phase Calculation
- Ephemeris Computation Utility
- Ephemeris Data File
- Arrival Time Correction

If you are interested in generating simulated LAT data, then you should study the 'Observation Simulation' threads.

- Observation Simulation Tutorial
- Orbit Simulation Tutorial
- Simulation Source Types

Over time additional threads will be added to all these categories, and the contribution of new threads will be welcome.

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2.2 *Fermi* Science Tools - Basic Concepts

There are certain basic concepts that you should know before you use the *Fermi* Science Tools. Here we do not summarize *Fermi's* instrument complement and their characteristics.

2.2.1 LAT Data

You will be analyzing a list of photons of astrophysical origin; the LAT instrument team will have analyzed each event that is telemetered to the ground, decided whether it is an astrophysical photon, and if so, characterized it by arrival time, apparent energy, and apparent origin on the sky. We say 'apparent' because this analysis does not reconstruct the photon's precise energy and incident direction. This list of photons is stored in a FITS file (FITS is described in section 3.1.2) called an 'event file' and given the .FT1 file extension.

Fermi will probably survey the sky most of the time, and even when the LAT is pointed at a particular point, sources over a large fraction of the sky will be observed simultaneously in the LAT's large field-of-view. Therefore one cannot distinguish between distinct LAT observations of a source. The LAT data are essentially one continuous list of photons from the beginning of the mission until the end with photons arriving from a large region of the sky at any given time. You the data analyst will select the photons you want to analyze from a given time range and spatial region. Because of the LAT's relatively large point spread function and the resulting necessity of analyzing not only the source of interest but also nearby sources, you will extract photons from a region ~20 degrees in radius.

To know where the LAT was pointed at any given time (and where the spacecraft was in its orbit), you need a FITS file called the 'spacecraft file' and given the .FT2 file extension. The spacecraft file also provides the livetime; this will indicate when the LAT was not actively taking science data during SAA passages. When you select the photons from a given time range, you will usually also extract a spacecraft file covering that time range.

The processing of the LAT events by the instrument team results in user-selectable analysis classes that are tailored for different types of analysis. These classes represent trade-offs between the number of counts that are considered photons, the non-photon background, and the size of the PSF. Currently three analysis classes are provided:

- The diffuse class provides the narrowest PSF at the expense of a smaller effective area.
- The source class should be considered the default.

- The transient class loosens the selection criteria, increasing the effective area at the expense of a larger PSF and a larger fraction of counts that do not result from photons.

The *Fermi* Science Tools calculate the LAT's instrument response functions for the different components of the selected analysis class based on the spacecraft file. You will be provided tools to explore the instrument response functions to give you a better understanding of the LAT's characteristics.

Therefore, almost all your analysis of LAT data will start with an event file (.FT1) with the photons from a region of the sky and a time range and a spacecraft file (.FT2) describing the LAT's pointing during the same time range.

2.2.2 *Fermi* GBM Data

Since the GBM is a burst detector, burst analysis will predominate. The basic GBM burst data will be 'Time Tagged Events' (TTE), lists of the detected photons from the different GBM detectors with their arrival times and apparent energies.

The GBM detectors have a relatively high non-burst background and therefore you will need background spectra. While there will be tools to create your own background, the GBM team will provide appropriate background files for each burst for each GBM detector.

The GBM instrument response for a given detector at a given time will be represented by the Detector Response Matrix (DRM). Since the spacecraft may slew during a burst to center the burst in the LAT's field-of-view, a given detector may require a series of DRMs for a burst. Again, a tool will be provided for you to calculate DRMs, and the GBM team will provide DRMs appropriate to each burst.

2.2.3 Analysis Environment

The *Fermi* Science Tools are an extension of the FTOOLS environment. Therefore almost all the tools can be run ‘ballistically’ from the command line. A ballistic tool is run by invoking the tool (e.g., typing its name at the operating system prompt) and entering its parameters. Once the parameter values are input, the tool proceeds without interacting with the user. Parameters can be input in a number of ways:

- The user can input all or some of the parameters on the command line.

- The user will be prompted for 'query' parameters that were not input on the command line. For each query the user is presented with the last value used; the user can accept this default by merely hitting a return. There are also 'hidden' parameters that can only be input on the command line.

- By adding 'mode=h' on the command line, the user can accept all the defaults (the last values used) except for parameters entered on the command line, without being queried. This input method supports scripting the tools into an analysis pipeline.

Many tools have a gui option that can be activated by including 'gui=yes' when invoking the tool at the command line. For example:
gtselect gui=yes

In addition, some tools will send plots to your screen. Currently **gtburstfit**, **gtlikelihood**, and **gtpsearch** have this feature. This option can be invoked by including 'plot=yes' on the command line. For example:
gtpsearch plot=yes

Data are input to, and output from, these tools as FITS files (FITS is short for 'Flexible Image Transport System'). FITS files consist of a series of units. Each unit has an ASCII 'header,' a list of 'keywords' and their values, followed by a data table. The data in the data table are described by keywords in the header. The first unit usually does not have a data table, and thus has only a 'primary header.' The subsequent units are called 'extensions.' FITS files can be read and modified by standard tools such as fv.

In addition to the ballistic FTOOLS, there are a number of tools that are run interactively.

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3 DATA

3.1 Data Files

3.1.1 Overview

The data that are telemetered from the *Fermi* spacecraft are not in a form that most users can use for astrophysical analysis. The telemetry is compact and difficult to parse. The instrument teams will process the data that is output from their instruments, producing lists of detected photons with the best estimates of the photons' characteristics. For the LAT, this entails starting with the signals from different components of the LAT resulting from interactions of charged particles, reconstructing the paths of the electron-positron pair produced when a gamma ray interacts with a tungsten atom in the LAT, and then calculating the gamma ray's arrival time, incident energy, and origin. The GBM processing assigns an average photon energy to the detector channels.

Therefore, processing by the instrument teams results in data that are ready for astrophysical analysis stored in a format that the software can read and that is easy to probe. The data from each instrument are described in greater detail elsewhere, but here we discuss the format. The data are stored as FITS files.

3.1.2 The FITS File Format

Almost all the files that are input to, or output from, the Science Tools are FITS files. FITS stands for 'Flexible Image Transport System,' and the format was originally developed to provide a standard image file format, but has been expanded to provide standards for many different file types used in astronomy. The *Fermi* Science Tools were developed to insulate the average user from the details of the file formats, but as always, additional knowledge can greatly augment your control over the analysis. The general FITS documentation online is extensive, but hopefully this overview will guide you in using this documentation.

FITS files consist of a series of one or more 'Header and Data Units' (HDUs), each of which contains an ASCII header followed by a binary table. The ASCII header describes the contents of the binary table (e.g., the column names and units), and thus the FITS files are largely self-defining. Headers have rows of text consisting of 8 character keywords followed first by the value of the keyword and then by a comment describing the keyword. The first ('primary') HDU is reserved for images, and often has no binary table and only a simple header (called the primary header) identifying the file (e.g., name, date of creation, mission). Subsequent HDUs are called 'extensions.' The de facto standard is that the header for an extension contains copious information pertaining to that extension.

There are standard FITS file formats, for example 'PHA' for a binned spectrum. These standard file formats have required extensions, and required keywords in the headers of these extensions. Similarly, there are standard extensions (with standard keywords)—such as EBOUNDS for storing an energy grid—that can be used in mission-specific file formats.

A number of tools exist to examine and manipulate FITS files. While we are attempting to create a system that does not require users to master a large number of additional tools, these FITS utilities will give you additional control over your analysis environment. The basic use of these tools is simple to learn. The FTOOLS have a series of tools—fcopy, fdump, fmodhead, fplot, and fverify—that allow you to examine, copy and manipulate FITS files. The tool 'fv' is a powerful GUI-based utility that should satisfy most needs to examine and modify FITS files. 'fv' will display images, but 'ds9' was designed specifically to display and manipulate images.

Finally, you might want to write software that reads or writes FITS files; the FITSIO libraries exist for many languages (e.g., C, C++, Fortran). Similar IDL FITSIO procedures also exist.

3.1.3 *Fermi* FITS Files

The *Fermi* FITS files were defined to comply with existing standards, particularly those of the Office of General Investigator Programs (OGIP). The OGIP houses the FSSC, similar organizations for RXTE, Swift, Suzaku, INTEGRAL, and XMM, and the HEASARC. Thus conformity with OGIP FITS file standards facilitates multi-mission tools, at least for high energy astrophysics, and assists scientists in analyzing data from different missions.

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3.2 LAT Data Products

3.2.1 Overview

The LAT astrophysical data analysis that you will perform with the *Fermi* science tools begins with a list of counts that have been identified as resulting from astrophysical photons. The analysis requires information about where the LAT was pointing and what was the observing efficiency. Therefore you will extract and manipulate two types of FITS files: the 'event file' and the 'spacecraft file.' These two filetypes have been given the file extensons .FT1 and .FT2, respectively.

3.2.2 Origin of the Photon Data

These two filetypes result from the processing of the data downlinked from the *Fermi* spacecraft (considered to be 'Level 0' data), and are therefore regarded as 'Level 1' data. For the LAT the Level 1 processing involves reconstructing the interaction of the event in the LAT from the 'hits' in the various parts of the LAT, identifying the type of event (e.g., astrophysical photon), and characterizing the event's relevant physical parameters (e.g., direction, energy). 'Hits' are the signals that result from the interaction of the event or its products with the various components of the LAT. The characterization of an event results in a set of ~200 parameter values forming the 'merit n-tuple.' Most of the events are not astrophysical photons, and most of the parameters describing an event are not relevant for the data analysis carried out by the science tools. Therefore, a small set of parameters for the counts considered astrophysical photons have been extracted from the event data to form the event file you will use for most astrophysical analysis. This optimal screened event list based on our current best knowledge of the instrument comprises our basic archived LAT data product.

Nonetheless, the full event dataset will always be available for users who wish to examine the full set of parameters of the astrophysical counts and also many events that are not included in the event files. The scientific community will be able to extract both file types from the databases of the FSSC.

3.2.3 Photon Classification

In reconstructing the events from the hits in the LAT, the LAT instrument team will make various cuts that will classify the events based on the probability that they result from photons and the quality of the reconstruction. The events will be separated into various event classes; each class will be characterized by its own set of instrument response functions. The reconstruction methodology and the event class cuts have evolved and are likely to continue so.

Currently there are three event classes. Intended for the study of diffuse emission, the 'diffuse class' has the smallest point spread function (PSF) and includes the smallest fraction of background counts; by being more restrictive, the diffuse class has the smallest effective area. The 'source class' is a superset of the diffuse class; by loosening the event selection cuts, the effective area is increased at the expense of including a higher fraction of background counts and photons with a larger PSF. The trade-off between effective area, background and PSF is favorable for analyzing point sources. Finally, the 'transient class' loosens the selection cuts even further (thus the transient class is a superset of the source class), increasing the effective area, especially below 250 keV, at the expense of a larger PSF and additional background events. This class is ideal for studying transients on timescales of less than an hour, such as gamma-ray bursts, because almost all the events originate in the source.

Each analysis class has its own effective area and point spread function, and the PSF varies with energy. Regardless of the analysis class you choose to include in your analysis, the Science Tools will use the instrument response functions appropriate to a given count in analyzing that count.

3.2.4 Contents of the Event Files

For each astrophysical photon the event file contains the following information (the list does not include all possible quantities):

- Energy—apparent energy of the event, in MeV
- RA—Right Ascension (J2000) of the photon's apparent origin, in degrees
- Dec—Declination (J2000) of the photon's apparent origin, in degrees
- L—Galactic longitude, in degrees
- B—Galactic latitude, in degrees
- Theta—inclination angle, the angle from the LAT's normal to the photon's apparent origin, in degrees
- Phi—azimuthal angle, the angle of the photon's apparent origin around the LAT's normal, in degrees
- Zenith Angle—the angle of the photon's apparent origin to the Earth-spacecraft vector, in degrees
- Earth Azimuth Angle—the angle of the photon's apparent origin around the Earth-spacecraft vector, in degrees
- Time—mission elapsed time, in seconds; the time convention is presented elsewhere
- Analysis Class—classification of the event

Note that additional information can be added to a FITS file, either as a keyword or an additional column, as long as its name differs from that of an existing type of data. Thus you might find additional information in event files.

3.2.5 Contents of the Spacecraft Files

The spacecraft files contain the following information for 30 second intervals (some intervals may be shorter):

- Start Time—beginning of the interval in Mission Elapsed Time
- Stop Time—end of the interval in Mission Elapsed Time
- Positions—position and orientation of the spacecraft and the LAT at the beginning of the interval in various coordinates
- McIlwain Parameters—two parameters that describe the strength and gradient of the Earth's magnetic field at the spacecraft at the beginning of the interval
- SAA Flag—indicates whether the LAT is not actively acquiring science data because *Fermi* is in the high radiation field of the South Atlantic Anomaly
- LAT Mode—the LAT's operational mode during the interval
- Livetime—the detector's livetime for the time interval

3.2.6 Other Files

In analyzing the LAT data you will use other files, some of which the tools access without your intervention, some of which are intermediate products of the analysis.

- Instrument Response Functions (IRFs)—the LAT's response is characterized by a number of functions with empirically determined parameters. The science tools access files with the parameters appropriate for a particular time period.
- Diffuse Emission Map—the LAT detects point sources on top of the bright diffuse emission from the Galaxy and extragalactic sources. The LAT team will provide one or more models of this diffuse emission, and the user will be able to substitute his/her own.
- Pulsar Ephemerides—a database of ephemerides of the pulsars that the LAT might detect.
- Livetime Cubes—over a specified time range, a livetime cube provides the t LAT livetime for a region of the sky at a given inclination angle (see the discussion in 'Precomputation of Likelihood Quantities'). Because the computation of these data is very time consuming, they are provided for specific time ranges.
- Source Definition—trial and fitted source models are stored in XML files (one of the few non-FITS files).
- Binned Spectra—the LAT photon data can be binned into spectra stored in the common 'PHA' format; this will be common for gamma-ray burst analysis.
- Bin Definitions—the grids used to bin spectra in time and energy can be input through FITS files.
- Response Matrices—to analyze binned spectra, the IRFs must be integrated over space and stored in the common 'RSP' format.

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3.3 GBM Data Products

3.3.1 Overview

The GBM astrophysical data analysis that you will perform with the *Fermi* science tools will focus on spectral analysis of gamma-ray bursts, and as with the LAT analysis, will begin with a list of counts. Remember that the GBM consists of 12 NaI detectors (8-1000 keV) and 2 BGO detectors (150 keV to 30 MeV).

The burst files and the daily files both include CTIME and CSPEC, files with counts binned with different time and spectral resolution. The time and energy binning described below are the current defaults, but both can be redefined in tables read by the flight software, and thus may vary during the mission.

3.3.2 Burst Files

The GBM team provides a series of files for each burst. This first set is crucial for spectral analysis.

- Time-Tagged Events—lists of the counts in 128 energy channels from each GBM detector for the period of the burst.
- Background Spectra—estimated background spectra for the period of the burst for each GBM detector. Although the GBM team will provide these background spectra, eventually the user will be able to generate his/her own backgrounds. Currently a constant background is provided, but eventually a polynomial model for the rate in each energy channel will be provided.
- Detector Response Matrices—the detector response mapping the input energy into the apparent count energy, provided for each detector with 128 energy channels as a function of time. The GBM team will provide these files. In the future, a tool will be provided so that users can create their own matrices.

The following set of files are also provided for each burst. However, they are not crucial for standard spectral analysis using the science tools.

- Catalog entry—the GBM team will calculate certain standard quantities, such as duration and fluence, and lightcurves of the spectral parameters. An initial catalog file will be provided with the other burst data products immediately after the burst, and updates will be provided later.
- CTIME and CSPEC (burst versions)—series of spectra with different temporal and spectral resolution from 4000 seconds before, to 4000 seconds after, the burst will be included. As currently planned, CTIME provides 8 channel spectra every 0.256 seconds and CSPEC 128 channel spectra every 4.096 seconds, with a higher time resolution of 1.024 s immediately after the trigger.

- TRIGDAT—the GBM team will package the burst alert telemetry, the information downlinked immediately after a burst.

3.3.3 Daily Files

The GBM team will provide a series of files every day.

- CTIME and CSPEC (daily version)—series of spectra with different temporal and spectral resolution, one per detector, each covering one day. Again, as currently planned, CTIME provides 8 channel spectra every 0.256 seconds and CSPEC 128 channel spectra every 4.096 seconds.

- Calibration and Housekeeping Files

3.3.4 Periodic Files

The GBM team will provide a series of files periodically.

- Catalogs—the burst catalog entries will be updated.

- Calibration—some calibration parameters will change slowly and will only have to be updated occasionally. Similarly, the modeling of the instrument response will be updated as the understanding of the detectors improves.

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3.4 Time in *Fermi* Data Analysis

3.4.1 Basic Principle

The *Fermi* Science Tools use mission elapsed time (MET), the number of seconds since the reference time of January 1, 2001, at 0h:0m:0s in the Coordinated Universal Time (UTC) system, corresponding to a Modified Julian Date (MJD) of 51910 in the UTC system.

3.4.2 Time Systems in a Nutshell

The Systeme International (SI) second is defined as the duration of 9,192,631,770 cycles of radiation corresponding to the transition between two hyperfine levels of the ground state of cesium 133.

Universal Time 1 (UT1) is the time system based on the rotation of the earth. Because of changes in the earth's rotation rate, in UT1 a day is not exactly 86400 s.

Coordinated Universal Time (UTC) provides a uniform-rate time system referenced to atomic clocks where a day is 86400 s. To keep UT1 and UTC within 0.9 s, a leap second is added to UTC as needed, typically every few years (see the USNO leap second history). UTC is the same as Greenwich Mean Time (GMT) or Zulu time (for the military).

Leap seconds can cause errors in measurements that straddle the addition of a leap second. The Terrestrial Time (TT) is a uniform rate time system referenced to the geoid without leap seconds. Effectively, TT time is greater than UTC time by a number that increases by 1 second every time a leap second is added to UTC. For *Fermi's* reference time of January 1, 2001, the difference was 64.184 s.

Another method of avoiding leap seconds over a time span of a number of years, such as the duration of the *Fermi* mission, is to use the number of seconds relative to a reference time. This is the method that astrophysical missions often use, where the number of seconds is called 'Mission Elapsed Time' (MET). Because MET and TT are both continuous uniform-rate time systems, MET and TT will always be offset from each other by a constant. Note that the time system should be included in specifying a reference time (e.g., whether the reference time is midnight on a particular date in the TT or UTC system).

The Global Positioning System (GPS) uses its own continuous uniform-rate time system that is related by a constant offset (13.184 s) to TT. The *Fermi* spacecraft uses a clock that is synchronized with signals from GPS satellites, and tags both housekeeping and science data with MET relative to January 1, 2001, 0h:0m:0s UTC.

The Julian Date (JD) is the number of days since Greenwich mean noon on January 1, 4713 B.C.E. Since JD is a large number—midnight at the beginning of January 1, 2008, corresponds to JD=2454466.5—and our calendar uses midnight as the beginning and end of a calendar day, the Modified Julian Date (MJD) has been defined as MJD=JD-2400000.5. Midnight (i.e., 0h:0m:0s) differs between the UTC and TT systems, and therefore one should specify whether a JD or MJD date is in the UTC or TT system.

3.4.3 Time in the *Fermi* Science Tools

The interface to the *Fermi* Science Tools uses MET, the number of seconds since midnight at the beginning of January 1, 2001, in the UTC system. Time is represented in the science data products as a double precision MET in seconds from the reference time given by the MJDREFI (the integer part) and MJDREFF (the fractional part) keywords in the FITS header. Although we use MET, which does not include leap seconds, we nonetheless want the science data to be in the TT system. Since the reference time is midnight in the UTC system, MJDREFF is non zero in the TT system. The same MJDREFI and MJDREFI is used by all science data products for both the GBM and the LAT. For our choice of reference time:

$$\text{MJDREFI}=51910$$
$$\text{MJDREFF}=7.428703703703703\times10^{-4}$$

In addition, the spacecraft clock drift for data obtained during periods when the GPS time signal is not available from the spacecraft can also be specified.

Because UTC corresponds to the time kept by everyday clocks, after correcting for the time zone, the ground system will use UTC.

In analyzing *Fermi* observations you may need to convert between MET and other time expressions such as Year-Month-Day, Year-Day of year, or MJD. The HEASARC provides a useful conversion tool for different missions including *Fermi*. Note that Swift also uses midnight, January 1, 2001, UTC as a reference time, and therefore the Swift and *Fermi* MET will be the same.

3.4.4 Additional Information

- The US Naval Observatory webpage on time systems
- Chandra's time tutorial
- RXTE's time tutorial
- Swift's time tutorial

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3.5 Data Access

3.5.1 Policy

The LAT event data are restricted to the LAT team during Phases 0 and 1, the first ~14 months of the *Fermi* mission. During these Phases, the LAT team will be turning on and calibrating their detector, and carrying out an all-sky survey. Summary information, such as spectra and lightcurves of ~23 sources of interest to the scientific community and of bright transient sources, is regularly released to the general. All the LAT event data will become public after the beginning of Phase 2.

GBM burst event data is made public from the beginning of the mission, although systematic uncertainties will likely be greater during Phases 0 and 1.

3.5.2 Extracting the Data

Once the LAT event data become public (at the beginning of Phase 2), you will use a webpage linked to both the FSSC website and the HEASARC Browse system. Browse is the HEASARC's web-based set of tables that are linked to the data from many high energy astrophysics missions. On this webpage you specify the desired selection criteria such as time range and spatial region. Use of this webpage should be self-explanatory. Soon after you submit the request you will be presented with a webpage with links to the event and spacecraft files that you can then ftp back to your computer. Information on the selection criteria are included in a FITS header in the event file; the Science Tools use this selection information.

The event files can be very large. If you use the ftp function built into your web browser, ensure that the browser's cache is large enough to accommodate the files; otherwise only part of the file may be read.

The GBM burst event data is available through Browse tables specific to *Fermi*. The data from each burst are packaged together with background files and response matrices.

3.5.3 Further Data Selections

Further data selections can be performed on the LAT event file that was extracted from the FSSC or HEASARC websites by using the **gtselect** tool. More refined selection criteria are available using this tool than when extracting the data through the data extraction website. The additional selection criteria are recorded in a FITS header in the resulting event file.

Subsets of the GBM TTE data are selected when binning these data for lightcurves or count spectra using **gtbin**.

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4 Software

4.1 The FTOOLS Environment

The *Fermi* Science Tools will be run within the FTOOLS environment. This means that most of the files that the tools read and write will be FITS files.

Those *Fermi* science tools that are FTOOLS can be run 'ballistically' from the command line. A ballistic tool is run by invoking the tool (e.g., typing its name at the operating system prompt) and entering its parameters. Once the parameter values are input, the tool proceeds without interacting with the user. Parameters can be input in a number of ways:

- The user can input all or some of the parameters on the command line.
- The user will be prompted for 'query' parameters that were not input on the command line. For each query the user is presented with the last value used; the user can accept this default by merely hitting a return. There are also 'hidden' parameters that can only be input on the command line.
- By adding 'mode=h' on the command line, the user can accept all the defaults (the last values used) except for parameters entered on the command line, without being queried. This input method supports scripting the tools into an analysis pipeline.

Note that the last value you used is the default for the next time you run a given tool. Parameter files ('PFILES') record all the parameter values you used the last time you ran the tool. When you install the *Fermi* science tools you will be provided with a set of parameter files that will include standard default values. Since hidden parameters are rarely changed (which is why they are 'hidden'), they will most likely remain at these standard default values.

As with all FTOOLS, a manual page can be summoned by typing 'fhelp toolname.' The manual page provided by fhelp will be the same as the relevant page in the Reference Manual.

The *Fermi* science tools are designed to be self-contained for basic analysis of *Fermi* data. The *Fermi* -specific tools are provided to the general scientific community through the FSSC website. However, you might want to use general purpose FTOOLS, the tools specific to other missions or associated astronomical tools (e.g., XSPEC); to use these other tools you will have to download and install the HEAsoft package separately. If you are at an institution with many astrophysicists and are using a server with a common library of astronomical software, then the HEAsoft package, and even the *Fermi* science tools, may already be installed for your use.

Later in the mission, as updates of the *Fermi* science tools become infrequent, these tools will be incorporated into the HEAsoft system, and then to install the *Fermi* tools the general scientific community will download and install the HEAsoft package.

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4.2 *Fermi* Science Tools File Structure

The *Fermi* science tools are installed via installation scripts, and if you follow the instructions presented in the instructions section of this documentation system, you should be able to process *Fermi* data without any knowledge of the files, libraries and system variables that comprise the analysis environment. However, a concept of what is included in this environment may help you use it, and should facilitate trouble-shooting. At the very least, an understanding of the file structure will explain what the installation of these tools has added to your computer, and what you should leave as-is.

The tools themselves are a series of binaries (files with the compiled programs) that are all in a /bin directory. This /bin directory must be in your 'path,' the list of directories that the operating system searches to find software you (or other software) invoke.

The tools use a set of libraries, some of which are specific to the *Fermi* science tools. These libraries are linked dynamically to the executable when the tool is run, and therefore the libraries are separate files in their own directory. These library directories must be in the appropriate path.

A parameter file is associated with each science tool that preserves the last value used for each input parameter; thus the last value you used when running that tool is the default when running the tool again. The installation of the tools provides an initial parameter file with common defaults. Thus, the hidden parameters will most likely remain at standard default values provided with the installation of the tools.

The parameter files are called PFILES, and they will be located in two directories. The first directory holds the 'system' parameter files, the defaults that are provided by the installation. The second directory holds the 'local' parameter files, your personal parameter files that are used when you (but not other users) use a tool. System variables provide the location of these directories.

If properly installed, the *Fermi* Science Tools can be run from any directory, and thus you should be oblivious to the tools' file structure!

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5 LAT Instrument Response Functions

5.1 LAT IRF Overview

The Instrument Response Function (IRF) is the mapping between the incoming photon flux and the detected events. 'Detection' depends not only on the LAT hardware but also on the processing that calculates the event parameters from the observables and assigns probabilities that an event is a photon. Indeed, different event cuts are planned based on tradeoffs between the non-photon background, the effective area and the spatial and energy resolution; these cuts result in analysis classes (see the section on LAT Data Products).

The IRF can be framed as an area times the probability that a photon with a given set of input parameters is detected as an event with a set of observables. For the LAT, the photon parameters are the energy E and the inclination angle φ (the angle between the LAT normal and the true source position) and the event is characterized by the apparent energy E' and the apparent source position φ'. Note that φ is an angle while φ' is a vector. Each analysis class has its own IRF. Our current formulation of the IRF is:

$$R(E',\varphi' ; E,\varphi)=A_{eff}(E,\varphi)p_{PSF}(\varphi' ;E,\varphi)\ p_E(E' ;E)$$

where A_{eff} is the effective area (with units of area), p_{PSF} is the PSF and p_E is the energy redistribution function. Again, φ is the inclination angle for the photon's actual direction while φ' is the vector for the photon's apparent direction. A number of assumptions are embedded in this formulation. The energy redistribution function is assumed to have no dependence on the actual or apparent inclination angles while the PSF has no dependence on the apparent energy. In addition, we assume that p_{PSF} is actually $p_{PSF}(\theta ;E,\varphi)$, where θ is the angle between the true and apparent source positions; thus we assume that the PSF is circular around the true source position.

The LAT IRF is determined by Monte Carlo simulations of the response of the LAT to a photon of energy E and inclination angle φ, and then reconstructing the resulting event. The comparison between the calculated properties of the event and the incoming photon gives the IRF. The three IRF functions—the effective area, PSF and energy redistribution—are presented in the subsequent sections. Resulting sensitivities are then presented.

The IRFs shown here represent the current prelaunch analysis. Undoubtedly the analysis classes and their IRFs will be optimized during after science operations begin. The latest plots of the IRF can be found at http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.

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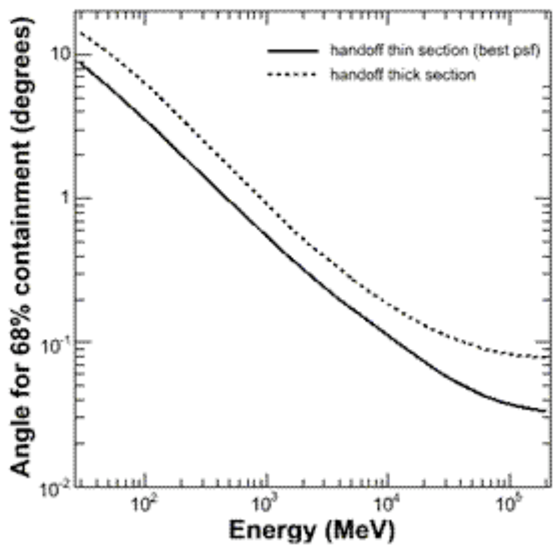
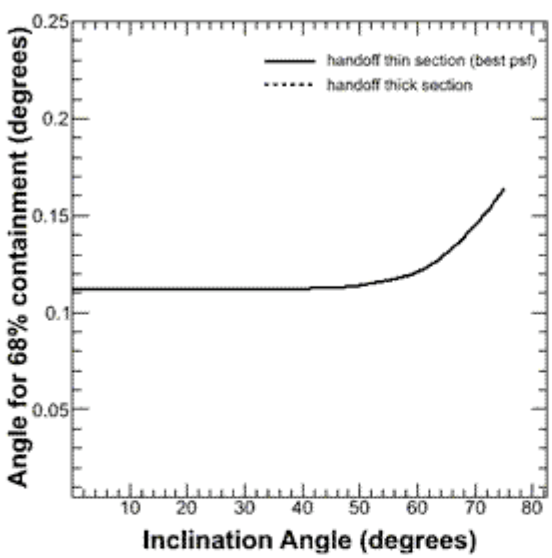
5.2 The Point Spread Function (PSF)

The LAT PSF is a function of an incident photon's energy and inclination angle, and the event class. The following plots show the PSF for the source class.

5.2.1.1 LAT 68% Enclosure Radii as a Function of Energy, On-Axis



5.2.1.2 LAT 68% Enclosure Radii as a Function of Inclination Angle, 10 GeV Photons



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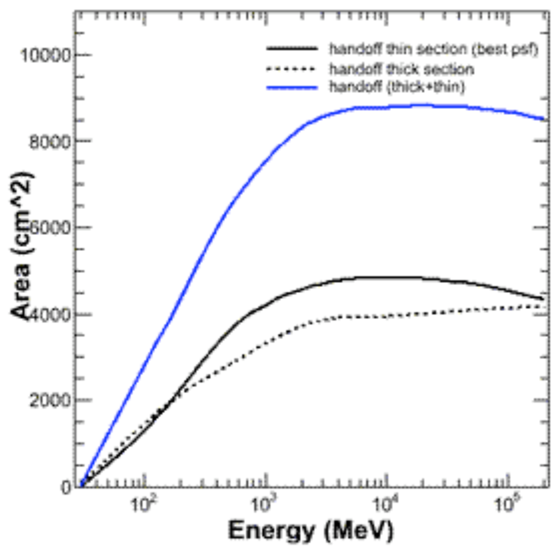
5.3 Effective Area

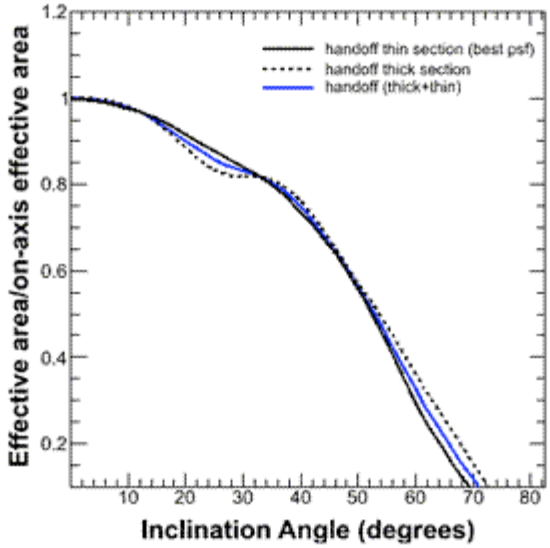
The LAT effective area is a function of an incident photon's energy E and inclination angle φ, and the event class. Note that the effective area does NOT take into account the deadtime, and therefore the observed count rate will be the effective area times the incident photon flux times the livetime fraction.

The following plots show the effective area for the source class. Note that 1 m^2 is 10^4 cm^2.

5.3.1.1 On-Axis Effective Area



5.3.1.2 Effective Area as a Function of Angle, 10 GeV Photons



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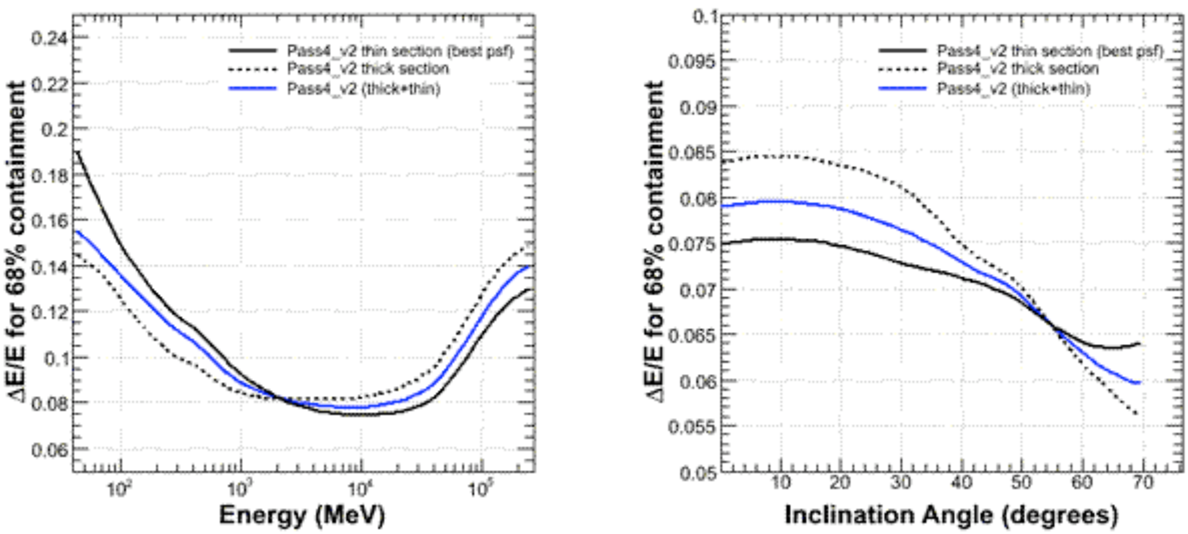
5.4 Energy Redistribution

The energy redistribution is of order 10%, while the LAT energy band is approximately 4 orders of magnitude (30 MeV to 300 GeV). Therefore, in many applications the energy redistribution can be neglected.

5.4.1.1 Energy Redistribution (68% containment) as a function of photon energy (left) and inclination angle for 10 GeV Photon (right)



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5.5 LAT Sensitivity

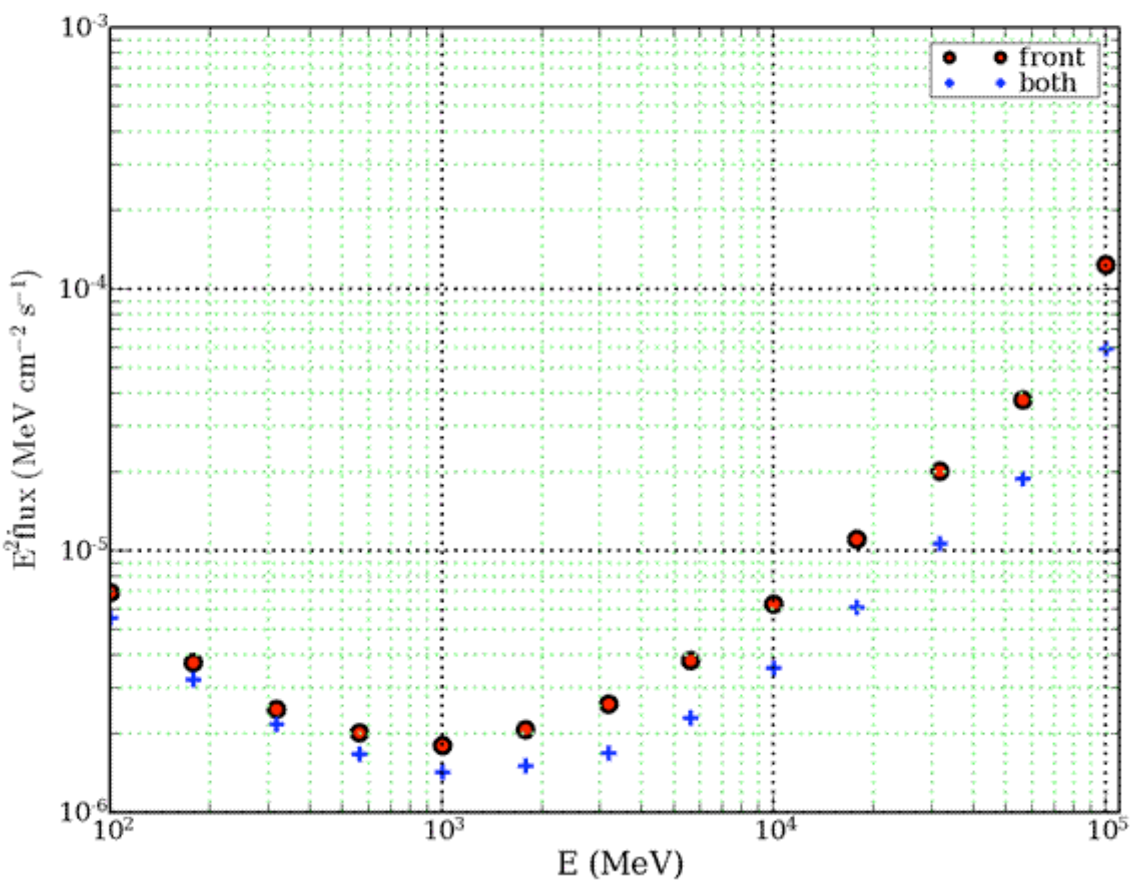
The point source sensitivity can be calculated from the LAT handoff IRFs. Note that the plots shown here are based on prelaunch analysis.

5.5.1 Differential Sensitivity

First we show the 5-sigma sensitivity to a high-latitude source whose spectrum is integrated over 1/4 decade in energy centered on the energy shown on the horizontal axis. Sensitivity is defined as the flux such that the log of the expected likelihood ratio for detection is 25 (or 5 sigma in the Gaussian case) and at least 5 photons. Thus, this plot shows the point source sensitivity using only the photons in each energy bin separately.

The assumptions are:

- One calendar year all-sky survey (including effects of the SAA and deadtime)
- Diffuse background flux 1.5x10-5/cm2/s/sr (E>100 MeV); spectral index -2.1

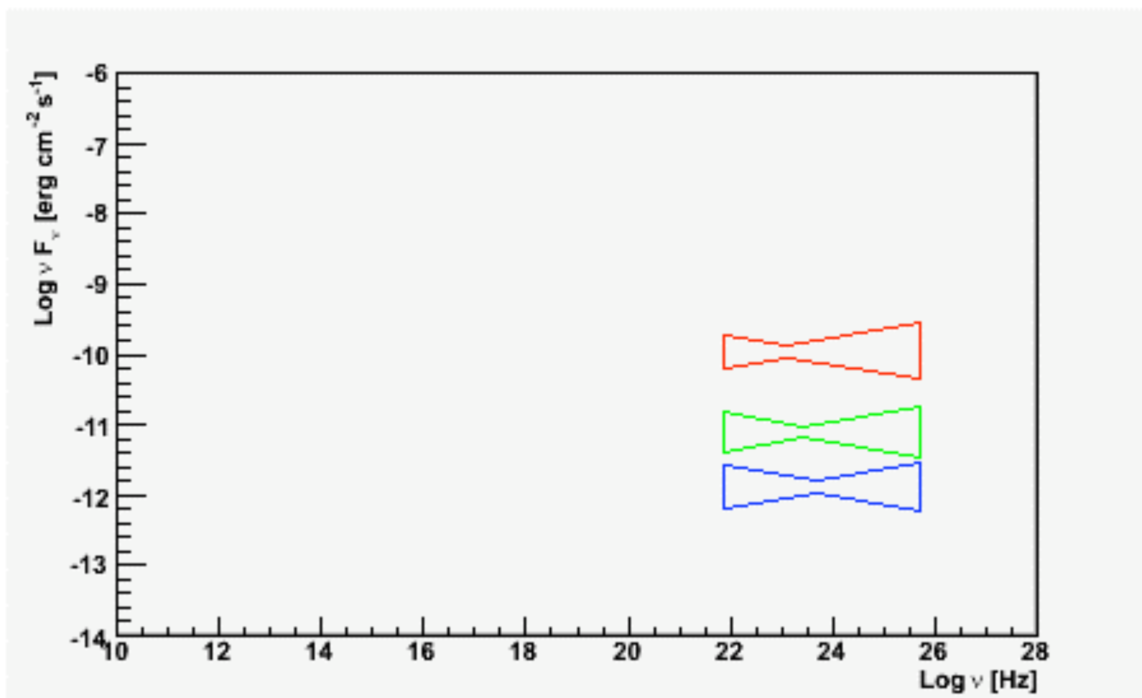


5.5.2 Integral Sensitivity

The point source sensitivity using the information in all energy bins is much better than the individual energy bin sensitivities above. We therefore provide the integral sensitivity measures in several ways.

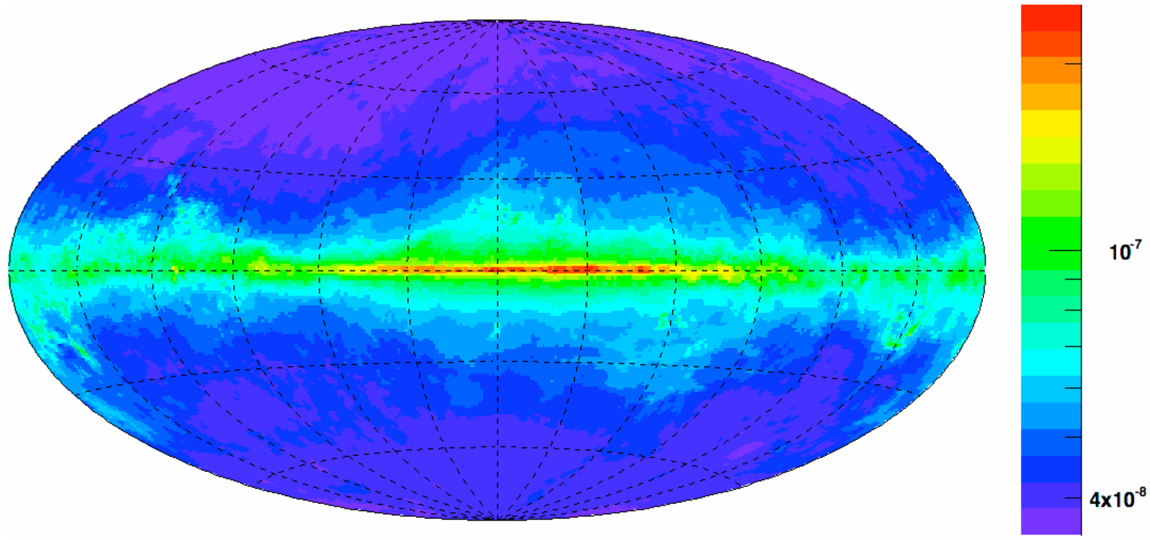
5.5.2.1 Fitted Sensitivity

First the bowtie plot, which shows the minimum needed for a 20% determination of the flux after a one-day, one-month, and one-year of operation in all-sky survey for a 1/E2 source. The resulting significance at each of these levels is about 8-sigma; the spectral index is determined to about 6%; and the bowtie shape indicates the energy range that contributes the most to the sensitivity. To make a measurement at that level or better, a flat spectral energy density curve must lie above the axis of the bowtie.



5.5.2.2 Sensitivity Sky Map

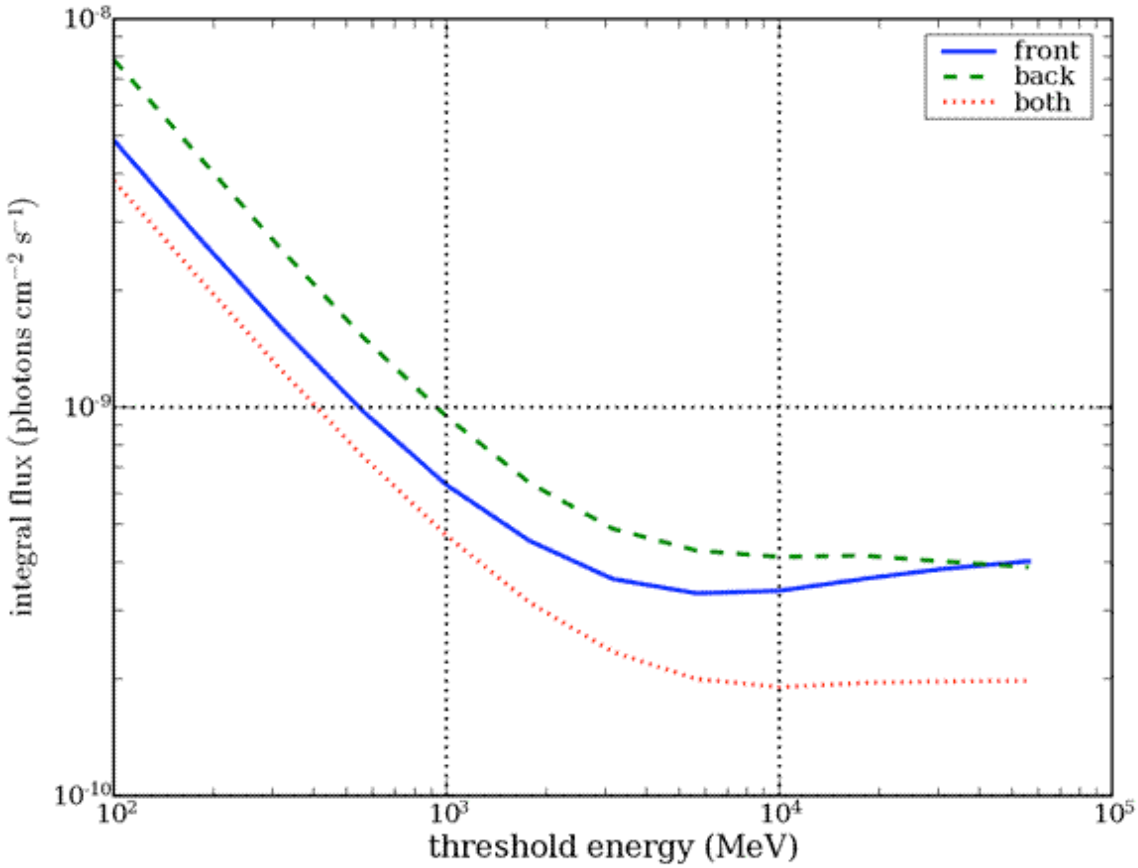
There are significant variations of the sensitivity in the sky due to the spatial structure in the diffuse galactic gamma-ray background. These are summarized in the map below, which shows the sensitivity across the sky in Galactic coordinates.



Aitoff projection of the sensitivity map for the 3-month LAT Bright Source List (shown in galactic coordinates)

5.5.2.3 Fitted Sensitivity

Finally, experiments are often compared using an integral sensitivity plot (5-sigma sensitivity for E>E0), assuming a 1/E2 spectrum source at high latitude. We show here an update for the *Fermi*-LAT:



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6 Data Exploration

6.1 Overview of Data Exploration

The quantitative analysis that detects sources and fits spectral parameters is often preceded by qualitative analysis that suggests that a source is present, or that a spectrum has an additional feature. This qualitative analysis involves selecting and then displaying data, and will depend on the data analyst's research style.

The fundamental LAT and GBM data are simple event lists, and data selection involves making cuts on the event lists. As discussed above, data selections can be made when extracting the LAT event list from the FSSC database, and further selections are made using the **gtselect** tool. Thus, for example, you can extract data for a source spanning a large time range, and use **gtselect** to break this event list into a series of shorter time ranges. You can extract LAT events from a large spatial area that includes a gamma-ray burst, and after localizing the burst, you can select the counts from a smaller area centered on the burst.

Many of these functions are usually performed by the HEASoft tool **xselect**, a complex tool that has many mission-specific features. **xselect** may eventually operate on *Fermi* data, but we have decided to first add a few simple *Fermi*-specific tools to the Science Tools package.

Once the data are selected, they can be displayed using standard display tools such as fv and ds9. Plotting individual counts as a function of position, time or energy may be revealing, but as the number of counts increases, binning the data becomes useful. For this purpose we have developed a binning tool, **gtbin**, that can bin both LAT and GBM data in time, energy and space. The products are FITS files; where relevant, standard formats are used (e.g., PHA and PHA-II for spectra), which again can be examined with tools such as fv or ds9.

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6.2 Lightcurves

We are interested in the source intensity as a function of time. Because this lightcurve is produced for data exploration, we will work in detector count space. The **gtbin** tool can create lightcurves for both LAT and GBM data using all the data in the event list (the event file data type for LAT data, the TTE data type for GBM data). Thus energy and spatial selections should be made prior to generating the lightcurve with **gtbin**. For LAT data, the energy and spatial selection occurs initially when the event file is extracted from the FSSC database and then by using **gtselect**.

Once you choose the **gtbin** option ('LC' for lightcurve), and name the input and output files, you specify the time binning. You have three choices:

- Linear temporal binning ('LIN')—you provide the start and stop times (in mission elapsed time—MET—described in the Time section) and bin duration.
- Constant signal-to-noise ratio in each time bin (the 'SNR' option)—you provide the start and stop times and the value of the signal-to-noise ratio.
- User specified time bins (the 'FILE' option)—you provide the name of the FITS file with the time binning. The **gtbindef** tool converts an ASCII file with the times into the properly formatted FITS file.

You can then plot the lightcurve stored in the output FITS file. For examples, see the 'Explore the LAT data,' 'Explore the LAT Data (Bursts),' and 'GBM Gamma-Ray Burst Analysis' threads.

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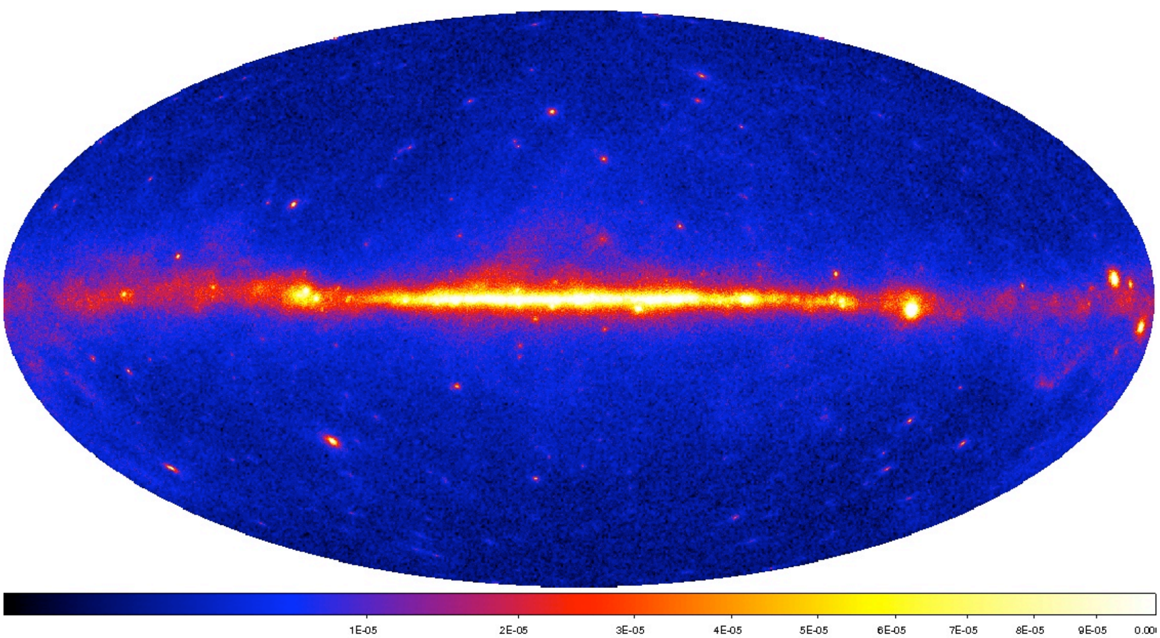
6.3 Count Maps

Here we want to create binned count maps for LAT data, the number of counts in spatial pixels. The **gtbin** tool can provide a count map in one energy band (the 'CMAP' option) or multiple energy bands (the 'CCUBE' option). The CMAP option bins all events in the event file, and therefore the energy band must be selected in creating the event file input to **gtbin**. For both options the event file must be created for the particular time range.

For both binning options you control the rectilinear spatial grid: the number of pixels in each direction, their size, the coordinate system, the center of the grid, and the type of projection. Ten projections are provided (see Calabretta & Greisen 2002, A&A, 395, 1077); AIT for 'Aitoff' is suggested.



Aitoff projection of the counts map for the 3-month LAT Bright Source List (shown in galactic coordinates)

You must also provide the energy bands used for the CCUBE option. You have three options:

- Linear binning ('LIN')—you provide the minimum and maximum energies and the number of bins.
- Logarithmic (the 'LOG' option)—you provide the minimum and maximum energies and the number of bins, and the software will calculate the bin edges. This will probably be your default.

- User specified energy bins (the 'FILE' option)—you provide the name of the FITS file with the energy binning. The **gtbindef** tool converts an ASCII file with the energy bands into the properly formatted FITS file.

The resulting output map files can then be viewed by fv or ds9. For examples, see the 'Explore the LAT data' and 'Explore the LAT Data (Bursts)' threads.

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6.4 Livetime and Exposure

Here we want to create exposure maps for LAT data, to see the amount of time the LAT spent observing your region of interest.

6.4.1 Livetime Cube

The LAT instrument response functions are a function of the inclination angle, the angle between the direction to a source and the LAT normal. The number of counts that a source should produce should therefore depend on the amount of time that the source spent at a given inclination angle during an observation. This livetime quantity, the time that the LAT observed a given position on the sky at a given inclination angle, depends only on the history of the LAT's orientation during the observation and not on the source model. The array of these livetimes at all points on the sky is called the 'livetime cube.' As a practical matter, the livetime cubes are provided on a healpix grid on the sky and in inclination angle bins.

Livetime cubes are calculated by the **gtltcube** tool. The inputs are size of the spatial grid (in degrees), the inclination angle binning (in cos τ steps), and the spacecraft file (FT2). **gtltcube** calculates the livetime cube for the entire sky for the time range covered by the spacecraft file, and therefore the same output file can be used for analyzing different regions of the sky over the same time range.

Livetime cubes are additive: the livetime cube for a time range that is the sum of two time subranges is the sum of the livetime cube for each of the time subranges. Thus, the livetime cube for five calendar days can be calculated by adding the livetime cubes for each of the five calendar days. Livetime cubes can be added by **gtltsum**.

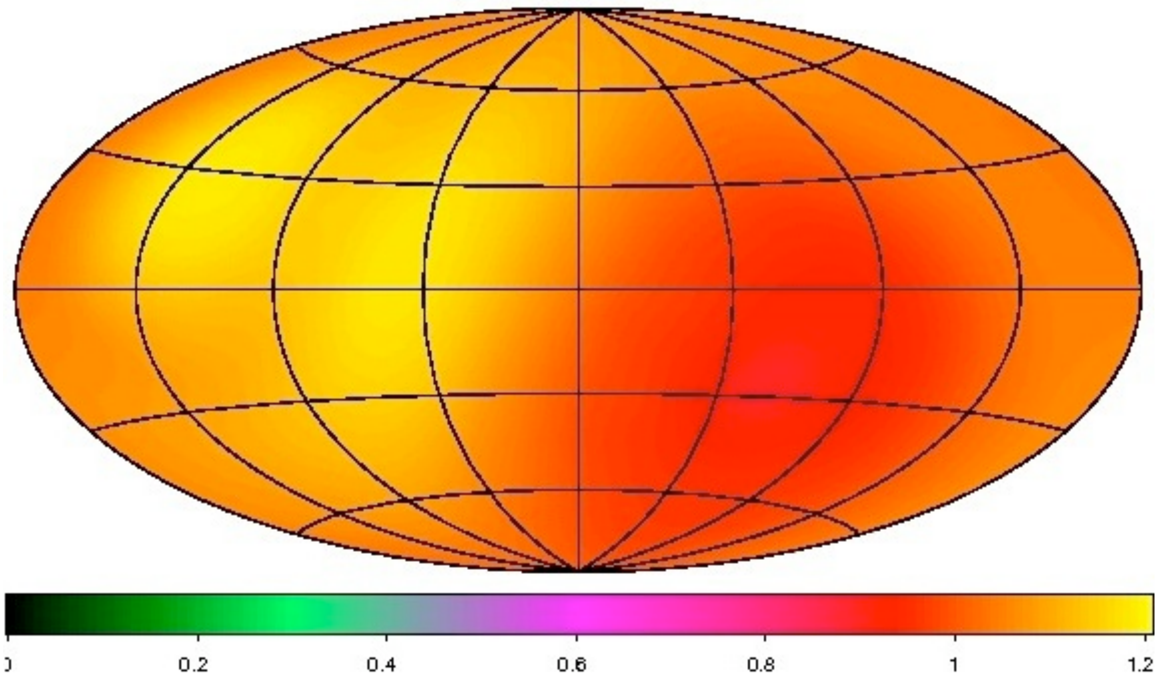
6.4.2 Exposure Maps

The exposure map is the total exposure—area multiplied by time—for a given position on the sky producing counts in your region of interest. Since the response function is a function of the photon energy, the exposure map is also a function of this energy. Thus the counts produced by a source at a given position on the sky is the integral of the source flux and the exposure map (a function of energy) at that position. The exposure map is used for extended sources such as the diffuse Galactic and Extragalactic backgrounds and not for individual sources.

The exposure map is calculated by the **gtexpmap** tool. The tool derives the Region of Interest from the observation's event file; remember that the region from which counts were selected is recorded by keywords in the photon file's FITS header. The Source Region is assumed to be centered on the Region of Interest, but the size of the Source Region must be input.

The **gtexpmap** tool needs the livetime spent at each inclination angle at every point in the Source Region; this can be provided by the livetime cube (as described in the previous subsection) or the tool will calculate these livetimes from the spacecraft file if no livetime cube file is provided. Note that the livetime cube is calculated on a spatial healpix grid while the exposure map is calculated on a longitude-latitude grid.

You control the rectilinear spatial grid: the number of pixels in each direction, their size, the coordinate system, the center of the grid, and the type of projection. Ten projections are provided (see Calabretta & Greisen 2002, A&A, 395, 1077); AIT for 'Aitoff' is suggested. You must also provide the instrument response function and the energy binning information: the energy range as well as the number of bins over which to perform the calculation. Binning is performed on a logarithmic energy scale.



Aitoff projection of the exposure map for the 3-month LAT Bright Source List (shown in galactic coordinates)

gtexpcube makes the maps, printing out the energy and effective area for each map generated as it goes. **Note:** These maps are mono-energetic, and represent the exposure at the energy specified, not integrated over the band pass. The resulting exposure map files can then be viewed by fv or ds9. For examples, see the 'Explore the LAT data' and 'Explore the LAT Data (Bursts)' threads. When you open the file, a "Data Cube" window will appear, allowing you to select between the various maps generated for each energy bin.

6.4.3 Combining Exposure

Generating each exposure map using **gtexpcube** is computationally intensive, as is combining these maps. Should you want to generate an exposure map covering multiple time intervals, it is recommended that you combine the livetime cubes using **gtltsum** prior to running **gtexpcube**, rather than combining the final exposure maps. **gtltsum** can only process a sum for two livetime cubes. So to sum more than two livetime cubes it will be necessary to run the **gtltsum** tool multiple times. Additionally, **gtltsum** will not allow you to overwrite an input file. Each filename must be unique.

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7 Likelihood Source Analysis

7.1 The Challenge of LAT Data Analysis

The astrophysical analysis of LAT data begins with a list of counts detected by the LAT. As described above, this list results from processing by the LAT instrument team that reconstructs events from the signals from different parts of the LAT, and categorizes these events as photon or non-photon. Note that we are calling events categorized as photons 'counts.'

While qualitative exploration of the data can suggest the presence of sources (i.e., by the spatial clustering of photons) and time variability, quantitative analysis requires fitting models to the data. This approach is necessitated by the LAT instrument's energy-dependent PSF and geometry-dependent effective area, by the nature of the gamma-ray sky backgrounds, and by the way the *Fermi* observatory is operated (scanning the sky in survey mode ~90% of the time).

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7.2 Likelihood Overview

To analyze LAT data, we construct the likelihood that is applicable to the LAT data, and then use this likelihood to find the best fit model parameters. These parameters include the description of a source's spectrum, its position, and even whether it exists.

7.2.1 The Likelihood Function

The likelihood L is the probability of obtaining the data given an input model. In our case, the input model is the distribution of gamma-ray sources on the sky, and includes their intensity and spectra. There is an implicit assumption that we understand sufficiently well the response of our detectors, in this case the LAT and the GBM, to the incident flux, in other words, that we have a sufficiently accurate mapping of the input model (the gamma-ray sky) to the data (the list of counts produced by either the LAT or the GBM).

Clearly, we expect a higher probability of obtaining the data from a model that is a better description of the underlying reality than from a model that is a poor description. At the same time we need to consider the plausibility of the models being compared; the data must favor a less plausible model more strongly before we accept that model. For example, few would consider a 30 percent discrepancy between energies calculated in an undergraduate laboratory course to be evidence for a violation of the conservation of energy.

The form of the LAT likelihood function will be discussed in the next section.

7.2.2 Model Fitting

In one of the most common applications, we know that a source is present, and we want to determine the best value of the spectral model parameters. Since we expect the best model to have the highest probability of resulting in the data, we vary the spectral parameters until the likelihood is maximized. Note that χ^2 is -2 times the logarithm of the likelihood in the limit of a large number of counts in each bin, and therefore where χ^2 is a valid statistic, minimizing χ^2 is equivalent to maximizing the likelihood.

A number of steps are necessary to fit a source's spectra; these are described in detail below.

1. Select the data. The data from a substantial spatial region around the source(s) being analyzed must be used because of the overlapping of the point spread functions of nearby sources.

2. Select the model. This model includes the position of the source(s) being analyzed, the position of nearby sources, a model of the diffuse emission, the functional form of the source spectra, and values of the spectral parameters. In fitting the source(s) of interest, you will let the parameters for these sources vary, but because the region around these sources includes counts from nearby sources

in which you are not interested, you might also let the parameters from these nearby sources vary.

3. Precompute a number of quantities that are part of the likelihood computation. As the parameter values are varied in searching for the best fit, the likelihood is calculated many times. While not strictly necessary, precomputing a number of computation-intensive quantities will greatly speed up the fitting process.

4. Finally, perform the actual fit. The parameter space can be quite large—the spectral parameters from a number of sources must be fit simultaneously—and therefore the likelihood tools provide a choice of three 'optimizers' (section 7.8) to maximize the likelihood efficiently. Fitting requires repeatedly calculating the likelihood for different trial parameter sets until a value sufficiently near the maximum is found; the optimizers guide the choice of new trial parameter sets to converge efficiently on the best set. The variation of the likelihood in the vicinity of the maximum can be related to the uncertainties on the parameters, and therefore these optimizers estimate the parameter uncertainties.

7.2.3 Source Localization

As mentioned above, the optimizers find the best fit spectral parameters, but not the location. In other words, the fitting tool does not fit the source coordinates. However, a tool is provided that performs a grid search—mapping out the maximum likelihood value over a grid of locations. As will be explained below, it is convenient to use a quantity called the 'Test Statistic' TS that is maximized when the likelihood is maximized.

7.2.4 Source Detection

The Test Statistic is defined as TS=-2ln($L_{max,0}/L_{max,1}$), where $L_{max,0}$ is the maximum likelihood value for a model without an additional source (the 'null hypothesis') and $L_{max,1}$ is the maximum likelihood value for a model with the additional source at a specified location. As can be seen, TS is a monotonically increasing function of $L_{max,1}$, which is why maximizing TS on a grid is equivalent to maximizing the likelihood on a grid. In the limit of a large number of counts, Wilkes Theorem states that the TS for the null hypothesis is asymptotically distributed as χ^2_x (here χ^2 is the distribution, not a value of the statistic), where x is the number of parameters characterizing the additional source. This means that TS is drawn from this distribution if no source is present, and an apparent source results from a fluctuation. Thus, a larger TS indicates that the null hypothesis is incorrect (i.e., a source really is present), which can be quantified. As a basic rule of thumb, the square root of the TS is approximately equal to the detection significance for a given source.

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7.3 The Likelihood Functional Form

We argued before that the LAT data will be binned into a great many bins because the counts are characterized by many variables. Thus, even with many counts, each bin will contain a small number of counts. The observed number of counts in each bin is characterized by the Poisson distribution, and with a small number of counts per bin, the Poisson distribution cannot be approximated by a normal distribution.

The likelihood *L* is the product of the probabilities of observing the detected counts in each bin. Assume that the expected number of counts in the *i*th bin is m_i. Note that m_i is a function of the source model, and will differ for different models. The probability of detecting n_i counts in this bin is $p_i=m_i^{n\_i}$ exp[-m_i]/n_i!. The likelihood *L* is the product of p_i for all *i*. But notice that this product factors into the product of the $m_i^{n\_i}$/n_i!, which depends on the data—the values of n_i—and the product of the exp[-m_i]. The product of exp[-m_i] for all i is equal to the exponential of minus the sum of m_i. The sum of m_i is just the total number N_{exp} of counts that the source model predicts should have been detected.

Therefore, the likelihood *L* can be factored into exp[-N_{exp}], which is purely a function of the source model, and the product of $m_i^{n\_i}$/n_i!, which is a function of both the source model and the data:

$$L = \exp[-N_{exp}] \prod_i m_i^{n\_i}/n\_i!$$

This likelihood, with finite size bins and n_i that may be greater than 1, is the basis for binned likelihood. Since binning destroys information (i.e., the precise values of the quantities describing a count), there is a tradeoff between the number of bins (and thus the bin size) and the accuracy; smaller bins result in a more accurate likelihood.

If we let the bin sizes get infinitesmally small, then n_i=0 or 1. The likelihood is now the product of exp[-N_{exp}], as before, and the product of m_i where *i* is now the index over the counts.

$$L = \exp[-N_{exp}] \prod_i m_i$$

Since m_i is calculated using the precise values for each count, and not an average over a finite size bin, this unbinned likelihood is the most accurate.

For a small number of counts the unbinned likelihood can be calculated rapidly, but as the number of counts increases the time to calculate the likelihood becomes prohibitive, and the binned likelihood must be used.

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7.4 XSPEC Analysis of *Fermi* Data

The XSPEC-type spectral analysis with which most high energy astrophysicists are familiar is a maximum likelihood analysis undertaken under special conditions. As we will show, these conditions usually will not apply to the LAT data. For the discussion here, 'XSPEC analysis' will refer to spectral analysis using XSPEC or a similar tool.

7.4.1 When an XSPEC Analysis is Valid

In XSPEC analysis the data consist of counts binned by energy in one dimensional vectors. For an imaging mission the analyst accumulates all the counts from a region surrounding the source into a count spectrum; these counts are binned in energy, either on the ground, or by the detector hardware onboard the spacecraft. No distinction is made between counts that are very close to the source or those on the edge of the accumulation region; forming the spectrum has destroyed information—where the counts were detected. Some missions, such as RXTE, by design accumulate spectra only, with no imaging information.

Thus the fundamental data set for an XSPEC analysis is a one-dimensional vector of counts in energy bins. An estimate of the background is usually subtracted from this count spectrum, resulting in a vector of the counts assumed to result from the source. A model of the source's flux distribution is run through a model of the detector, producing a vector of the counts that would have resulted if the source model were correct. The source model is then varied until the agreement between the observed and actual are sufficiently close (χ^2 is minimized). This process assumes that the number of counts in each energy bin will have a normal (Gaussian) distribution with an expectation value equal to the model counts.

However, where the number of counts in an energy bin is small, as is often the case for LAT photon data, we need another statistic for finding the best fit, and we usually do not have a goodness of fit measure. In addition, for LAT analysis we want to consider where the counts fall relative to the point source—counts that are further from a source are less likely to originate from that source. Thus we want to use software that was constructed to consider multi-dimensional data.

7.4.2 The LAT Data and the Conditions for XSPEC Analysis

In most applications the analysis of LAT data *must* be multi-dimensional. The LAT PSF is large (~3.5 degrees) at low energy (~100 MeV), and small (<0.15 degrees) at high energy (~10 GeV). With the LAT's large effective area (>0.8 m^2), many sources will be detected near the analyzed source(s); i.e. their PSFs will merge at low energy. In addition, the LAT's FOV is large—usable counts can be accumulated from over 65 degrees off-axis—and with the large PSF, distant sources will influence the modeling of a given source. For example, to model a given source, the sources within a few PSF radii must be modeled since some of the counts from these sources will fall near the source of interest. But to model these sources, the sources a few PSF radii further out must be modeled.

Obviously the influence of a source becomes attenuated with distance, but as a result of the large FOV, distant sources do influence the analysis. Finally, the spatially varying diffuse background must be included in the analysis. Therefore the analysis must be three dimensional—two spatial and one spectral.

The instrument response (PSF, effective area, energy resolution) is currently a function of energy, inclination angle (the angle between the source and the LAT normal) and photon category. Since the LAT is usually in sky-survey mode, a source will be observed at different inclination angles. Each count is therefore characterized by a different instrument response function (IRF). It is feasible to sum the counts from a given direction and form an IRF weighted by the fraction of the observation that occurred at a given inclination angle, but a great deal of information will be lost. For example, counts for which the PSF is small will be mixed with counts for which the PSF is large. Therefore, it is best to maintain the inclination angle as one of the observables characterizing a count.

Each count is therefore characterized by many observables, for example, the apparent energy, the apparent origin, the inclination angle, and the event category. If one forms bins with finite widths in each of these observable dimensions, then the number of bins will be very large. Even if many counts are accumulated, the number of counts in each bin will be small, in many cases only 0 or 1. Statistical treatments that assume that the distribution in each bin is Gaussian, or near Gaussian, are usually inadequate.

Thus the conditions under which an XSPEC analysis can be undertaken usually do not apply to the LAT data: the data usually must be treated as multi-dimensional and cannot be binned into one-dimensional bins or with sufficient numbers of counts per bin. However, XSPEC analysis of LAT data would be justified when the data can be binned into a one dimensional count spectrum with sufficient counts per energy bin. An XSPEC analysis should be valid for a few strong sources that dominate any surrounding sources (e.g. a high galactic latitude AGN in a flaring state) and for fluent gamma-ray bursts (few background counts are expected within the PSF during the short burst duration).

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7.5 Choosing the Data to Analyze—Regions of Interest and Source Regions

What data should be used for source analysis? Assume that you are interested in analyzing the spectrum of a single source. Because of the large point spread function at low energies (e.g., 68% of the counts will be within 3.5 degrees at 100 MeV), you want to use the counts within a region around your source. Nearby sources will contribute counts to this region, and you will probably want to model them, that is, to model a single source you may be forced to model a handful of sources. And therefore you may need to include counts from an even larger region.

For the greatest accuracy possible in modeling a single source you should model the entire sky! This will usually not be feasible. And in reality, the influence of sources a very great distance away from your source will be greatly attenuated. Thus, you should include sources from a large 'Source Region' and counts from a smaller 'Region of Interest' (ROI). The positions and spectra of sources in the Source Region outside of the ROI must have been obtained previously, for example from a catalog; you include these sources for their contribution to the counts in the ROI. How you treat the sources in the ROI is under your control. You may wish to fix the parameters of the sources other than the one you are studying at their catalog values, or you might want to perform a fit on the parameters of all these sources. This will be discussed at greater length below.

Therefore, you will use all sources in the Source Region. You will determine the size of the Source Region appropriate for your needs from experience and experimentation; we recommend default values of ROI+10 and ROI+5 degrees for sources dominated by ~100 MeV and ~1 GeV events, respectively. You will include all counts in the ROI. Again, you will determine the appropriate ROI size from experience and experimentation, but we recommend default values of 20 and 15 degrees for sources dominated by ~100 MeV and ~1 GeV events, respectively.

Although we discussed data selection above, here we summarize the tools available in the *Fermi* Science Tools package. When you extract the LAT data from the online database, you will be able to choose the time range, spatial region and energy range from which the counts are extracted. The result is an event file (.FT1) with these counts, and a spacecraft file (.FT2) describing the position of the spacecraft and the orientation of the LAT over the chosen time range. The spatial region is the Region of Interest (ROI). You can perform further selections with the **gtselect** tool. Note that the data selection criteria are recorded in the photon file with 'Data Sub-Space' (DSS) keywords.

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7.6 Model Selection

The models used by the Science Tools are stored in XML files. XML (short for eXtensible Markup Language) is a language to define and store data; HTML used to define webpages is a form of XML. XML files are ASCII files full of 'tags' delimited by the < and > symbols.

For historic reasons the Science Tools use two XML formats, one used for parameter fitting (e.g., by the likelihood tool) and the other for source simulation. The likelihood XML format includes parameter uncertainties but does not allow time dependence while the simulation format does; in addition, the simulation format includes source models that are not in the likelihood format.

7.6.1 Creating and Editing Source Models

You could master the syntax to create a model XML file, and indeed occasionally you might find it convenient to edit an existing XML file. However, a GUI-driven tool called ModelEditor is included in the Science Tools. This tool is invoked at the command line, and its use is fairly intuitive. ModelEditor can read and write XML files of both formats. Here we point out fundamental features of this tool, focusing on the creation of likelihood XML files.

While you might want to define each source in your Source Region, it is easier to start with a catalog for this region. Prior to the release of the first-year catalog, the obvious choice is the 3EG (3rd EGRET) catalog. Under 'File' choose 'Extract...' This will open a GUI that allows you to define your Source Region (RA, Dec and radius in degrees), the flux limit, the file with the catalog (the 3EG catalog is the default) and the output file. Remember, the Source Region should be larger than the Region of Interest, the region for which there are counts. You will then be presented with a GUI with a list of selected sources. Selecting a source presents you with the source properties: a position and a spectral model. You can edit these values; for example, the catalog may have assumed the spectrum was a simple power law, but you would like to try a power law with an exponential cutoff. You save the model for a particular source by clicking the 'Set components' button.

Using the pull-down menu you can delete a selected source or add either a diffuse or point source.

The entire source model need not be in the same XML file. The tools accept lists of source XML files, both at the command line and by reading in simple ASCII files listing the XML files.

The model parameters (in the likelihood XML format) have a number of attributes:

- value—the parameter's value; may be an initial guess or the result of a fit

- scale—a scale factor for the parameter
- name—name given to the parameter
- max—parameter's maximum value
- min—parameter's minimum value
- free—whether the parameter should be fit: 0 means the parameter value should be fixed, 1 that it should be fit

Therefore, if the 'value' is '4.3' and the 'scale' is '1e-9,' the actual parameter value is 4.3×10^{-9}.

7.6.2 Spatial Models

You have a choice of four models:

- SkyDirFunction—a point source
- ConstantValue—a diffuse source with a constant flux per steradian
- SpatialMap—a spatially varying diffuse source. The map of the source is provided by a file. The default is the map of the Galactic Diffuse Emission.
- MapCubeFunction—a 3 dimensional FITS map (two sky coordinates and energy) used to map diffuse emission, thereby allowing arbitrary spectral variation as a function of sky position

7.6.3 Spectral Models

The units for the spectral models are $cm^{-2}\ s^{-1}\ MeV^{-1}$ for point sources and $cm^{-2}\ s^{-1}\ MeV^{-1}\ sr^{-1}$ for diffuse sources. All energies are in MeV.

You have a choice of the following models:

- PowerLaw—simple power law

$$N(E) = N_0\ (E/E_0)^{\gamma}$$

  - N_0—Prefactor
  - γ—spectral index
  - E_0—energy scale

- BrokenPowerLaw—two component power law

$$\begin{aligned} N(E) &= N_0\ (E/E_b)^{\gamma_1} \quad ; \quad E<E_b \\ &= N_0\ (E/E_b)^{\gamma_2} \quad ; \quad E>E_b \end{aligned}$$

  - N_0—Prefactor
  - γ_1—low energy spectral index
  - γ_2—high energy spectral index
  - E_b—break energy

- PowerLaw2—simple power law with the integral number of counts between two energies as the normalization

$$N(E) = (\gamma+1)N\,E^{\gamma}/[E_{max}^{\gamma+1} - E_{min}^{\gamma+1}]$$

  - N—Integral number of counts between E_{max} and E_{min}
  - γ—spectral index
  - E_{min}—low end of energy range (always a fixed quantity)
  - E_{max}—high end of energy range (always a fixed quantity)

- BrokenPowerLaw2—two component power law, with the integral number of counts between two energies as the normalization

$$N(E) = N_0(N,E_{min},E_{max},\gamma_1,\gamma_2)\ (E/E_b)^{\gamma_1} \quad ; \quad E<E_b$$
$$= N_0(N,E_{min},E_{max},\gamma_1,\gamma_2)\ (E/E_b)^{\gamma_2} \quad ; \quad E>E_b$$

$N_0(N,E_{min},E_{max},\gamma_1,\gamma_2)$ is the normalization necessary for N counts between E_{min} and E_{max}

  - N—total number of counts between E_{min} and E_{max}
  - γ_1—low energy spectral index
  - γ_2—high energy spectral index
  - E_b—break energy
  - E_{min}—lower energy limit for number of counts
  - E_{max}—upper energy limit for number of counts

- LogParabola—curving function used to model blazars

$$N(E) = N_0\ (E/E_0)^{(\alpha+\beta \ln(E/E_0))}$$

  - N_0—Prefactor
  - α—spectral index
  - β—index
  - E_b—break energy

- ExpCutoff—power law with a modified exponential cutoff. This function can be used both for simple exponential cutoffs and to model the absorption by the extragalactic background light (EBL).

$$N(E) = N_0(E/E_0)^{-\gamma}\exp[-(E-E_b)/p_1-p_2\ln(E/E_b)-p_3\ln^2(E/E_b)] \quad ; \quad E > E_b$$
$$N(E) = N_0(E/E_0)^{-\gamma} \quad ; \quad E < E_b$$

  - N_0—Prefactor
  - γ—spectral index

- E_0—pivot energy
- E_b—break energy
- p_1—exponential energy scale
- p_2—parameter
- p_3—parameter

- BPLExpCutoff—an exponentially cut-off broken power law

$$
\begin{aligned}
N(E) &= N_0\,(E/E_b)^{\gamma_1} \quad ; \quad E<E_b \text{ and } E<E_{abs} \\
&= N_0\,(E/E_b)^{\gamma_1}\exp[-(E-E_{abs})/E] \quad ; \quad E<E_b \text{ and } E>E_{abs} \\
&= N_0\,(E/E_b)^{\gamma_2} \quad ; \quad E>E_b \text{ and } E<E_{abs} \\
&= N_0\,(E/E_b)^{\gamma_2}\exp[-(E-E_{abs})/E] \quad ; \quad E>E_b \text{ and } E>E_{abs}
\end{aligned}
$$

- N_0—Prefactor
- γ_1—low energy spectral index
- γ_2—high energy spectral index
- E_b—break energy
- E_{abs}—energy of cutoff onset
- E_0—exponential energy scale

- Gaussian—function that can model an emission line.

$$N(E) = [N_0(2\pi)^{-1/2}/\sigma]\exp[-(E-E_0)^2/2\sigma^2]$$

- N_0—Prefactor
- E_0—center energy
- σ—width

- ConstantValue—constant-value function.

$$N(E) = N_0$$

- N_0—Prefactor

- BandFunction—function used to model gamma-ray burst spectra

$$
\begin{aligned}
N(E) &= N_0\,(E/E_{piv})^{\alpha}\,\exp[-E(2+\alpha)/E_p] \quad ; \quad E<(\alpha-\beta)E_p/(2+\alpha) \\
&= N_0\,[E_p(\alpha-\beta)/(\alpha+2)E_{piv}]^{(\alpha-\beta)}\exp[\beta-\alpha](E/E_{piv})^{\beta} \quad ; \quad E>(\alpha-\beta)E_p/(2+\alpha)\ E_{piv}
\end{aligned}
$$

- N_0—normalization
- α—low energy spectral index
- β—high energy spectral index
- E_p—'peak' energy, energy of peak of νf_ν spectrum

- FileFunction—tabulated function, F(E), with free-floating normalization. The function is provided in an ASCII file with two columns. The first column is the energy in MeV, and the second is the flux (cm^{-2} s^{-1} MeV^{-1} for a point source, cm^{-2} s^{-1} MeV^{-1} sr^{-1} for a diffuse source)

$$N(E) = N_0F(E)$$

  - N_0—Prefactor

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7.7 Precomputation of Likelihood Quantities

The computation of the likelihood usually occurs many times. Fitting involves varying model parameters until the best values are found (the methodology is described elsewhere). Fits are done with various model parameters fixed or with different sources present or absent. Certain quantities need be calculated only once, speeding up the repeated computation of the likelihood.

7.7.1 Livetime Cubes

The LAT instrument response functions are a function of the inclination angle, the angle between the direction to a source and the LAT normal. The number of counts that a source should produce should therefore depend on the amount of time that the source spent at a given inclination angle during an observation. This livetime quantity, the time that the LAT observed a given position on the sky at a given inclination angle, depends only on the history of the LAT's orientation during the observation and not on the source model. The array of these livetimes at all points on the sky is called the 'livetime cube.' As a practical matter, the livetime cubes are provided on a healpix grid on the sky and in inclination angle bins.

Because livetime cube calculation is computationally intensive, the FSSC will provide livetime cubes on different timescales. Thus to analyze data from a given time period, you will download livetime cubes from the FSSC spanning most of this period, run **gtltcube** for the time not covered by these pre-packaged livetime files, and then sum all these livetime cubes with the **gtltsum** tool (see Livetime and Exposure section).

7.7.2 Exposure Maps

The likelihood consists of two factors: the first is dependent on the detected counts and differs between binned and unbinned likelihood calculations; and the second is equal to the exponential of the negative of the expected total number of counts N_{exp} for the source model. The exposure map is the total exposure—area multiplied by time—for a given position on the sky producing counts in the Region of Interest. Since the response function is a function of the photon energy, the exposure map is also a function of this energy. Thus the counts produced by a source at a given position on the sky is the integral of the source flux and the exposure map (a function of energy) at that position. The exposure map is used for extended sources such as the diffuse Galactic and Extragalactic backgrounds and not for individual sources.

The exposure map should be computed over a Source Region that is larger than the Region of Interest by ~50%. This is necessary to insure that all source photons are included due to the size of the LAT instrument PSF at low energies.

7.7.3 Diffuse Emission and Individual Counts

The term in the likelihood dependent on the counts is a function of the probability of observing each count. This probability is the sum of the probability from all sources, both point and diffuse. The **gtdiffrsp** tool calculates the contribution of diffuse sources to this probability. The event file lists the position of all counts. The spacecraft file provides the history of the inclination angle for all positions from which the diffuse emission originates, and the source model describes the diffuse emission.

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7.8 Likelihood Model Fitting

We now have all the inputs necessary for fitting parameters using the likelihood tool, **gtlike**:

- An event file with the counts to be fit.
- A spacecraft file that covers the time range over which the counts in the event file were extracted.
- A source model.
- Precomputed quantities, such as the livetime cube and the exposure map.

Fitting involves finding the set of parameters that maximizes the likelihood. Since the likelihood is a non-linear function of the parameters, algorithms for maximizing non-linear functions can be used. The maximum is found by iteratively calculating the function for different sets of trial parameters; by estimating derivatives of the function with respect to the parameters, the algorithms choose new trial parameters that are progressively closer to the set that maximizes the function. The function is calculated for new sets of trial parameters until the change in the function value between iterations is sufficiently small (or the number of iterations reaches a maximum value). While iterating, these algorithms map out the dependence of the function on the parameters, particularly near the function's maximum. The uncertainties on the best fit parameters are related to this dependence. Different algorithms vary in how rapidly they converge to the function maximum, the amount of computer memory they require, and the accuracy with which they map out the dependence of the function on the parameters near the maximum (and thus estimate the uncertainty).

In running **gtlike** you have a choice of algorithms, called optimizers, for maximizing the likelihood. The details of each algorithm are beyond the scope of this document. But as a rule of thumb, you should use DRMNFB followed by NEWMINUIT. DRMNFB is efficient at finding the maximum likelihood but approximates the parameter dependence near this maximum; consequently, the uncertainties provided by this optimizer may not be reliable. On the other hand, NEWMINUIT is a conservative optimizer that converges more slowly than these other methods, and indeed may exhaust the number of permitted iterations before convergence. However, NEWMINUIT more accurately maps out the parameter space near the likelihood maximum, and thus provides more reliable uncertainty estimates.

Thus a reasonable strategy is to run **gtlike** with the DRMNFB optimizer until convergence, and then to run **gtlike** using the NEWMINUIT optimizer with the best fit parameter values from this first run in order to calculate the uncertainties on the parameter values.

The convergence criteria is controlled by the hidden variable 'fit_tolerance' whose definition depends on the particular optimizer but is approximately the fractional change in the logarithm of the likelihood.

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7.9 Source Detection and Localization

As discussed in the overview of the likelihood method, the likelihood tool, **gtlike**, currently does not fit the source position parameters. Instead, the **gttsmap** tool runs **gtlike** at each gridpoint on a rectangular grid. You provide a model of all the other sources in the Source Region, and **gtssmap** calculates the Test Statistic (TS) for adding an additional source at each gridpoint. The livetime cube and exposure map that can be precomputed for running gtlike can also be used for **gttsmap**. The user should be aware that **gttsmap** is computationally intensive, and could require many hours to run to completion.

If you have a good approximate source location, such as the gridpoint with the maximum TS from **gtssmap** or a candidate source identification, then you can refine the location by running **gtfindsrc**, which maximizes the TS in continuous space.

The TS is -2 times the logarithm of the ratio of the likelihood for the model without the additional source (the null hypothesis) to the likelihood for the model with the additional source. Thus the TS is maximized when the likelihood for the model with the source is maximized. Thus the location with the maximum TS is the best fit source position.

But is the addition of this source significant? By Wilks' Theorem, if there is no additional source then the TS should be drawn from a χ^2_n distribution, where n is the difference in the degree of freedom between the models with and without the additional source. In our case the additional source is characterized by a source intensity and spectral index (the spectrum is assumed to be a power law), and thus n=2. Wilks' Theorem is valid asymptotically as the number of counts increases, and studies are underway to determine the number of LAT counts for a typical analysis is sufficiently large. If Wilks' Theorem is valid then integrating χ^2_2 from the observed TS value to infinity gives the probability that the apparent source is a fluctuation. The resulting significance is $\sim(TS)^{1/2}\sigma$, and thus TS=25 is equivalent to 5σ.

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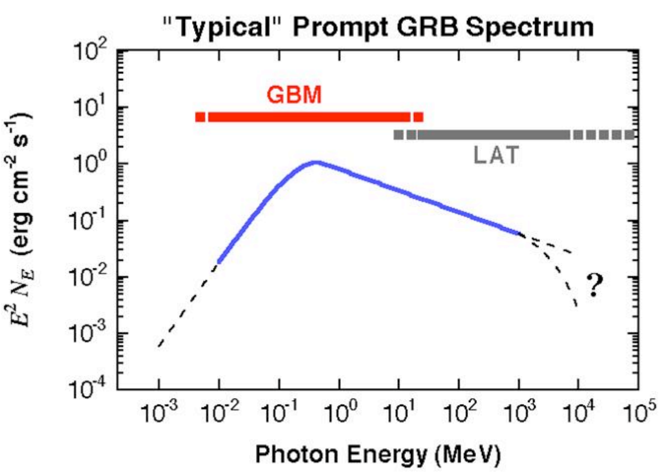
8 Gamma-Ray Burst Analysis

8.1 Overview of GRB Spectral Analysis

The duration of the prompt burst emission—the ~100 keV component—is (relatively) short, tens of seconds at most. Therefore, the LAT's pointing does not change significantly during the burst, and all the counts can be treated as having one response function. Within a PSF radius of the burst position less than one non-burst count per minute is expected. The count rate over the FOV is ~2 Hz, the LAT's FOV is approximately 2 steradians, and the PSF has a radius of ~3.5 degrees at 100 MeV. Consequently, we expect ~0.01 Hz non-burst photons or 0.7 cts/minute within a PSF radius. Therefore, we can treat all counts within 1-2 PSF radii as burst photons.

Since a) all the counts within a PSF radius of the burst originated in the burst, and b) all the counts have the same response function, multi-source spatial analysis is unnecessary for spectral analysis of LAT data! However, spatial analysis might be necessary for localizing the burst. All the counts within a PSF radius and within a time range can be binned into a count spectrum (apparent energy is the single dimension), and traditional spectral analysis can be applied to the resulting series of LAT count spectra.

Since both the LAT and GBM data consist of lists of counts, we are free to choose the same temporal binning for burst data from both detector types, and then perform joint fits on the binned one dimensional spectra.



Gamma-ray burst spectral coverage of the GBM and the LAT

The afterglow will most likely produce a small number of counts accumulated over timescales of tens of minutes to hours. Thus afterglow data must be analyzed with the general likelihood tool for LAT data analysis. Here we present binned spectral analysis.

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8.2 Binned GRB Spectral Analysis

8.2.1 Method

Gamma-ray burst spectral analysis takes advantage of the unique properties of this phenomenon: a relatively short transient from a point source. For the LAT there will usually not be competing emission from other sources in the field-of-view, while the GBM cannot distinguish spatially between burst photons and those originating from other sources. Therefore, the analysis is one dimensional: we determine the input burst flux from the apparent energies of the events that triggered the detector (for the purposes of this discussion we call these events 'counts'). In binned spectral analysis the apparent energies are binned. For the GBM there is little choice because the measured energies are binned by the hardware, while for the LAT we will assume there are sufficient counts per bin.

For the LAT we select all the counts from a region 1-2 PSF-radii around the burst position from the time range which includes the burst; these counts are then binned into energy channels. These counts should all originate from the burst because estimates of the non-burst event rate predict about one count within a PSF-radius per minute.

For the GBM the origin of the counts is unknown, and therefore all the counts from the burst's time range are selected. The counts consist of photons originating from the burst and background from other sources, both astrophysical and instrumental. The background is usually estimated from the count rates before and after the burst. The GBM will have already binned the counts into predetermined energy channels.

The selected counts may be further binned in time. The result is then a series of count spectra that will be analyzed. In general each count spectrum is fitted independently.

Consider a count spectrum c_i, where the index i runs over energy channels. This count spectrum is the sum of the burst flux convolved with the detector response and the background b_i. We sample the photon flux striking the detector in different energy channels f_j, where the index j runs over energy channels (NOT necessarily the same channels as the count spectrum!). The response function can be simplified into a mapping between the photon's true energy and the count's apparent energy. With the counts and the fluxes expressed as vectors, the response function is a matrix D_{ij}, the 'Detector Response Matrix' (DRM) in the burst community (frequently called the 'RSP'). The resulting matrix equation is

$$c_i = D_{ij}f_j+b_i$$

where summation over j is assumed. Since D_{ij} is not a square matrix, and even if it is, it is usually nearly singular, this equation cannot be solved by inverting D_{ij} but requires 'forward folding.' Note that for the LAT b_i~0 but for the GBM b_i is substantial, and in many channels will dominate the burst counts.

In forward folding a model flux vector f'_j is folded through the response, resulting in a model count spectrum c'_i. The underlying model flux is usually an analytic function (e.g., a power law) with a small number of spectral parameters (e.g., normalization and spectral index for a power law flux model). The model c'_i is compared to the observed c_i, and then a new model flux vector f'_j is calculated, usually by varying the spectral parameters. This iterative process ends when the model c'_i is sufficiently close to the observed c_i, resulting in best-fit spectral parameters.

'Sufficiently close' is usually determined by minimizing chi^2. A sufficiently small value of chi^2, e.g., comparable to the number of degrees-of-freedom, indicates that the fit is satisfactory. If the number of counts per bin is not large enough to assume that they are drawn from a Gaussian distribution, then the Cash statistic should be used instead of chi^2.

If two or more detectors observe the same burst at the same time, then the counts recorded by each detector resulted from the same input burst spectrum. Thus, we can require that the count spectra for each detector be fit by the same flux model. The result is a joint fit.

8.2.2 LAT Analysis

The LAT data consist of photons. To use the techniques described above, these events must first be binned. The steps in the analysis are as follows:

- Extract the photons from a region around the burst at the time of the burst. The selection of the photons occurs both in the extraction of the data from the database and using the **gtselect** tool.
- Bin the photons with **gtbin**. You choose the energy bins either interactively (bins that are uniform in photon energy or the logarithm of the photon energy) or through a binning file. The time bins can be also be chosen interactively or through a binning file. The time bins can be uniform in time, have a constant signal-to-noise ratio per bin, or be Bayesian Blocks. The binning files are created either by a previous run of **gtbin** or using the **gtbindef** utility. The output of the binning is a PHA or PHAII file, standard FITS filetypes.
- Create the DRM with **gtrspgen**. The output is a RSP file, also a standard FITS filetype.
- Fit the resulting spectra with an analysis tool such as XSPEC. The inputs are the PHA and RSP files created above. Note, no background file!

The 'LAT Gamma-Ray Burst Analysis' thread leads you through this analysis step-by-step.

8.2.3 GBM Analysis

The GBM data also consists of individual events (here called 'counts'). Once again, they must be binned.

- Bin the counts with **gtbin**. The GBM detectors will have already binned the counts in energy. Once again the time bins can be chosen interactively or through a binning file. Three interactive time binning methods are available: uniform in time; constant signal-to-noise ratio per bin; or Bayesian Blocks. The binning files are created either by a previous run of **gtbin** or using the **gtbindef** utility. The output of the binning is a PHA or PHAII file, standard FITS filetypes.

- Fit the resulting spectra with an analysis tool such as XSPEC. The input are the PHA or PHAII file created above and the RSP and background files provided with the burst data.

The 'GBM Gamma-Ray Burst Analysis' thread leads you through this analysis step-by-step.

8.2.4 Joint Fits

A major hurdle for joint fitting has always been getting spectra from different detectors with the same time bins. But because the *Fermi* data are event lists, we can just bin the data with the same time bins. The binning tool **gtbin** can output a file with the time bins used to bin an event list, and can read a binning file to bin an event list. Therefore:

- Bin the data from one detector, for example using constant signal-to-noise ratio bins. These time bins should be output in a binning file.
- Use the resulting binning file to bin the event data from the other detectors.
- Fit the spectra simultaneously with an analysis tool such as XSPEC; most such tools are capable of performing joint fits. In most cases the relative normalization between detectors should be added as a fitted parameter to compensate for errors in the effective areas of the different detectors.

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9 Pulsar Analysis

9.1 Pulsar Analysis Overview

Many of the sources that the LAT detects, particularly close to the Galactic Plane, may be gamma-ray pulsars. Determining whether a source is a pulsar entails searching for a periodicity in the source's flux, and thus is not affected by the spatial overlap of counts from adjoining sources (these nearby sources contribute an unpulsed flux). However, the photon flux detected by the LAT from most pulsars is be low; for example, one photon is expected to be detected from every 500 pulses of the Crab pulsar. Therefore the analysis of most suspected pulsars requires year-long accumulations of the counts from the region surrounding the source. This analysis is very sensitive to the pulsar ephemeris.

For most pulsars in the LAT data a blind period search can be computationally intensive. Consequently, the *Fermi* mission has initiated a monitoring campaign of the radio and optical pulsars that are candidates for pulsed gamma-ray emission. The ephemerides resulting from this campaign are provided in a database included as part of the standard *Fermi* Science Tools installation.

The database provided by the *Fermi* mission is the default database used by the pulsar tools. This default can be overridden by specifying a different database using the hidden parameter 'psrdbfile' in running the pulsar tools. For example, to use the pulsar ephemeris database file 'master_pulsardb_v3.fits' (assumed to be in your working directory) in the **gtpsearch** tool, type 'gtpsearch psrdbfile=./master_pulsardb_v3.fits' on the command line.

The Science Tools package includes a suite of pulsar analysis tools to determine whether a LAT source is a pulsar known at other wavelengths, refine the ephemeris, and assign spin and orbital phases to every count. Users can then use other *Fermi* science tools and standard FTOOLs to analyze the pulse-dependent spectrum, plot the pulse profile, etc.

The analysis of a candidate pulsar begins with the extraction of counts from the region surrounding the LAT source. In contrast to the likelihood analysis, only the counts from within a few degrees are required because the surrounding sources and background do not have to be modeled at this stage of the analysis. For example, a user may select the count list that maximizes the signal-to-noise ratio.

The *Fermi* observatory is not an inertial frame, and changes in its position during the observation will affect the photons' arrival time. The 'barycentric correction' compensates for this motion. The pulsar tools calculate this correction and modify the times in the event file; you can run the **gtbary** tool independently.

The barycenter-corrected counts can now be searched for pulsations. In most cases the source will be suspected of being a known pulsar, with a candidate spin ephemeris. Thus **gtpsearch** performs a limited search of ephemerides around the candidate ephemeris, which can be entered by the user or extracted from the *Fermi*-provided database. Note that even when the LAT source has been definitively identified as a known pulsar, the ephemeris can be refined using **gtpsearch**. A 'blind search' tool, **gtpspec**, is also provided.

The Science Tools package includes tools for assigning spin pulse phases and binary orbital phases, and for manipulating the FITS files that store the pulsar ephemerides.

The count list used to determine whether pulsations are present may not be appropriate for other pulsar analyses. For example, the standard likelihood analysis will be necessary for phase-dependent spectroscopy because the counts originating in nearby sources must be considered. All count lists used for pulsar analysis must be barycenter-corrected.

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9.2 Barycentric Correction

Ideally a detector in an inertial frame should observe a pulsar in an inertial frame. However, *Fermi* is not in an inertial frame: the spacecraft is in orbit around the Earth, which in turn is in orbit around the Sun. In addition, the spacecraft is in the gravitational potential well of the Earth and of the Sun, resulting in general relativistic effects. The pulsar may be in a binary system, with the resulting effects from the binary orbit and gravitational potential well. The transformation from *Fermi's* frame to an inertial frame and from the pulsar's frame to an inertial frame can be achieved by 'correcting' the arrival time of a photon produced by the pulsar to what it would have been had it been emitted and received in inertial frames. Since the Solar System is assumed to be nearly in an inertial frame—the System's acceleration is assumed to be negligible—the correction places the hypothetical ideal receiver at the Solar System's barycenter, hence this correction is called the 'barycentric correction.' Note that Jupiter's mass displaces the Solar System's barycenter so that it is slightly outside the Sun.

The transformation to inertial frames can be broken into a number of physical effects. Since these effects are small relative to the travel time from the pulsar to *Fermi*, they can be added linearly. Analysis of the relative magnitudes of these effects show that the dominant effects result from the difference in photon travel time and the potential well of the Earth and Sun.

The photon arrival times are usually converted in a series of steps, resulting in sequence of different time systems:

Conversion	**Convert from**	**Convert to**	**Light travel time**	**Time system conversion**
Geocentric correction	Mission Elapsed Time	Geocentric time	±23 ms (at maximum)	From Mission Elapsed Time to Terrestrial Time (TT)
Barycentric correction	Geocentric time	Barycentric time	±500 s (at maximum)	From TT to Barycentric Dynamical Time (TDB)
Binary demodulation	Barycentric time	Binary-demodulated time	Depends on binary parameters	None

The *Fermi* pulsar tools carry out this arrival time correction using *Fermi*-specific routines based on the FTOOL faxbary; faxbary has been thoroughly tested and used for various other missions. The position of the Earth relative to the Solar System barycenter is calculated from JPL Planetary Ephemeris DE-405.

It is also possible to compute a geocentric corrected event list, to which you may apply your own barycentering and subsequent analysis.

For micro-second precision timing, relativistic effects are not negligible. Such effects include: the Shapiro delay in the Solar System, aberration due to the motion of the spacecraft around the Earth and the motion of the Earth around the Sun, and relativistic delay at the source (for binary pulsars only). These effects are included in the *Fermi* Science Tools.

9.2.1 Performing the Barycentric Correction

To perform the barycentric correction we need the list of photon arrival times, the position of the spacecraft at these times, and the pulsar's position in the sky. Thus, the user must supply the tool with an event file (with the arrival times), a spacecraft file (with a history of the spacecraft position), and the RA and Dec of the pulsar.

The Science Tools replace the arrival time for each count in the input event file with the corrected arrival times. Thus the input and output event files have the same name, and *the tool's operation is irreversible*.

The time range in the spacecraft file must begin before, and end after, the time range in the event file; the beginning or end times of these two time ranges should not be the same.

The Science Tools assume that the spacecraft position in the spacecraft file is given in meters. This will normally not be a concern since the software that creates the spacecraft file follows this convention. However, if you create a new spacecraft file, or modify an existing one, do not use a different length unit (e.g., centimeters or kilometers) for the position.

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9.3 Limited Frequency Search

In many cases you will be analyzing a LAT source coincident with a known pulsar using an ephemeris determined at other wavelength bands. Thus, the frequency (or period) search can be restricted to ephemerides around a trial ephemeris.

A number of statistics have been created to test whether a time series is periodic with a specified frequency or period:

- Chi-squared test (Leahy et al. 1983, ApJ, 266, 160; Vaughan et al. 1994, ApJ, 435, 362)
- Zn^2 test (Buccheri et al. 1983, A&A, 128, 245)
- Rayleigh test (equivalent to Zn^2 test for n = 1)
- H test (De Jager et al. 1989, A&A, 221, 180)
- Bayesian approach (Gregory and Loredo 1992, ApJ, 398, 146; Gregory and Loredo 1996, ApJ, 473, 1059)

Currently the first four tests have been implemented in the *Fermi* Science Tools. These tests calculate the phase for each count, and then evaluate the distribution of phases for non-uniformity; if the signal is not periodic at the tested frequency, then the distribution should be uniform (same number of counts in each phase interval). A phase can be calculated even when the frequency (or period) varies, either because of intrinsic spin variability or the pulsar is in a binary. As a result, each of the above tests can be applied to a specific set of values for the frequency and frequency derivatives (or period and period derivatives). Of course, if you are searching for the set of values most consistent with the data, the more parameters considered, the larger the space that must be searched.

These tests determine whether the signal can be described by a specific ephemeris that may involve more than one parameter. As implemented in the **gtpsearch** tool, the user-specified test is carried out on a grid of frequencies (or periods) centered on a trial value with user-specified constant values of the first and second derivatives of the frequency (or period). For example, a user may apply the chi-squared test to counts from a suspected pulsar at 100 frequencies around 30 Hz with a frequency derivative of 0, then at the same 100 frequencies with a frequency derivative of 10^{-9} s^{-2}, etc.

9.3.1 Running gtpsearch

The *Fermi* tool for a limited frequency search is **gtpsearch**; examples of running the tool can be found in the Period Search analysis thread. This tool can be run by the user in either frequency or period space. The discussion here assumes that the search is in frequency space; running the tool in period space is similar. Internally the tool translates a period search into a frequency search.

The limited frequency search is applied to the arrival times of the counts contained in an event file; these counts should have been extracted from the region around the source suspected of being a pulsar.

The limited frequency search will be centered on a trial frequency. This frequency can be input manually, or may be extracted from a pulsar ephemerides database. The *Fermi* pulsar tools use a specific FITS pulsar ephemerides database file format. Your Science Tools installation will include a database provided by the *Fermi* mission of pulsar ephemerides of pulsars that may be detectable in the LAT's energy band.

- To input the trial frequency manually, run **gtpsearch** and at the "How will spin ephemeris be specified? <DB|FREQ|PER>" query enter 'FREQ' to specify the ephemeris type.
- To use a trial ephemeris from a database, include 'psrdbfile=filename' on the command line. At the 'Pulsar name' query enter the name of the pulsar, and then at the "How will spin ephemeris be specified? <DB|FREQ|PER>" query enter 'DB'.

The default is to input the central value of the frequency grid that will be tested, and the spacing and number of gridpoints. Frequencies are given in units of Hz, and periods in units of second. The gridpoint spacing is in units of the Fourier frequency, the inverse of the dataset's total time range. If you include 'cancelpdot=yes' on the command line when calling **gtpsearch**, you will also input the first and second derivatives of the frequency. But remember, the periodicity test is carried out on a grid of frequencies at these constant values of the frequency derivatives.

An ephemeris includes a time origin, which determines when the phase is 0 and when the instantaneous frequency is equal to the constant part of frequency (i.e., the frequency is a Taylor series around the time origin). When searching for the frequency the absolute phase is unimportant, and therefore the time origin in not necessary for the phase. Similarly, if the frequency derivatives are zero then the time origin is not necessary for specifying the frequency. However, if there are frequency derivatives, then the time origin must be specified. Regardless of whether it is necessary, you will always input the time origin; you may enter a specific time, or choose the beginning (TSTART), end (TSTOP), or midpoint (MIDDLE) of the data's time range.

You will input parameters for your choice of periodicity test:

- Chi^2—The chi-squared test bins the phases of the counts and compares the number of counts in each phase bin to the average (the total divided by the number of bins). Therefore the user has to specify the number of phase bins to be used in the analysis.
- Zn^2—This test determines the strength of the harmonics across the range of phases. Thus, the n=1 component looks for a simple sinusoidal variation, n=2 tests for two evenly spaced peaks, etc. The n=1 test is also called the Rayleigh test.
- H—This test is Zn^2-test with n automatically optimized for the data.

The output consists of text with the result of the periodicity search and an optional plot. The output includes the significance of the maximum value of the periodicity statistic, which is the probability of obtaining this maximum value if no periodicity is present (i.e., the null hypothesis); the probability includes the number of trials, the frequency range tested in units of the Fourier frequency. This tool does not create an output file.

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9.4 Spin Pulse Phase

The **gtpphase** tool calculates the pulsar phase for each count in an event file and adds a column containing that information; the Pulse Phase Calculation analysis thread demonstrates how the tool is run. This is a standard operation, but a *Fermi*-specific tool is provided to interact with the *Fermi*-specific files.

Important note: since the pulsar phases should be calculated for the photons' arrival time at the Solar System barycenter, the arrival times in the event file should be barycenter corrected before **gtpphase** is run.

As with the limited period search tool **gtpsearch**, the ephemeris can be input manually (e.g., after finding an ephemeris using **gtpsearch**), or may be extracted from a pulsar ephemerides database. In particular, your Science Tools installation includes a database provided by the *Fermi* mission of ephemerides of pulsars that may be detectable in the LAT's energy band.

- To input the ephemeris manually, run **gtpphase** and at the "How will spin ephemeris be specified? <DB|FREQ|PER>" query enter 'FREQ' or 'PER' to indicate you want to enter a frequency-based or period-based ephemeris.
- To use an ephemeris from a database, include 'psrdbfile=filename' on the command line. At the 'Pulsar name' query enter the name of the pulsar, and then at the "How will spin ephemeris be specified? <DB|FREQ|PER>" query enter 'DB'.

The tool adds the spin phase to each count in the event file; each count is a row in the FITS file, and **gtpphase** adds a PULSE_PHASE column. If the pulsar database file includes a binary ephemeris for the pulsar, the spin phase includes the effect of the binary motion on the spin phase. No information is lost, but the input and output file names are the same. If the tool runs successfully, no additional output results.

Standard FITS tools can now be used to manipulate and display the pulse data. For example, **fhisto** can bin the pulses, and the resulting pulse profile can be plotted with **fplot**. Similarly, cuts on the data could be made with **fselect.**

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9.5 Orbital Phase

The pulsar may be in a binary, and thus photons can be assigned both a pulsar spin and a binary phase; the **gtophase** tool assigns an orbital phase to each count. The Binary Orbital Phase Calculation analysis thread demonstrates how this tool is run. Once again, the arrival times in the event file should be barycenter corrected before the tool is run.

In this case the binary ephemeris must be extracted from a pulsar ephemerides database, such as the database provided by the Science Tools installation. As with **gtpsearch** and **gtpphase**, enter 'psrdbfile=filename' on the command line, and at the 'Pulsar name' query enter the name of the pulsar. As with **gtpphase**, the input and output files are the same. An ORBITAL_PHASE column will be added to the output file.

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9.6 Pulsar Ephemerides Databases

A FITS file format has been defined for pulsar ephemerides databases. This format is based on the ephemerides files used to analyze EGRET data. These files can be used to input ephemerides into *Fermi* tools such as **gtpsearch**, **gtpphase** and **gtophase**. In particular, the *Fermi* mission maintains a pulsar ephemerides database for pulsars detected at non-gamma-ray energies that may be detected in the LAT's energy band; this database is part of the standard Science Tools installation. You should update this database from time to time.

Because the spin frequencies of most pulsars vary with time, an ephemeris is valid for a specific time period. Even when the ephemeris includes the derivatives of the frequency, the ephemeris validity is limited by 'glitches' and other noise in the pulsar rotation, and inaccuracies in the determination of the frequency and its derivatives. Because the LAT's detection rate of pulsar photons will be low and accumulation times of pulsar counts will be long, analysis of LAT pulsar data will be particularly sensitive to changes in the pulsar frequency; therefore you should ensure that the pulsar's spin ephemeris is applicable to the data's time range.

The pulsar ephemerides files may include multiple names for a given pulsar, such as a colloquial name (e.g., 'Crab'), the 'B-name' and the 'J-name.' However, the exact spelling (including spaces) of one of these names must be used.

The *Fermi* Science Tools installation includes tools to query and manipulate pulsar databases. The pulsar ephemeris database file, master_pulsardb_v3.fits (current for Science Tools revision v9r8p2), is available from the FSSC.

9.6.1 Querying a Pulsar Database

The primary purpose of the **gtephem** tool is calculating the spin ephemeris of a pulsar at a user-specified reference time. But as the Ephemeris Computation Utility analysis thread shows, this tool can serve many additional purposes.

When the **gtephem** tool is run, the file with the pulsar ephemerides is specified with the psrdbfile parameter on the command line. You are queried for the pulsar name and the reference time (the Mission Elapsed Time at which the spin ephemeris should be calculated). The tool then calculates the spin ephemeris for this reference time; the spin ephemeris output to the screen includes the pulse phase, pulsar frequency (Hz), and the first and second frequency derivatives. If the ephemeris database file includes an ephemeris for a binary orbit, the effects of the binary orbit on the spin ephemeris at the reference time will be included.

The tool returns an error message if the database does not include a pulsar with the input name. By including 'strict=yes' on the command line, the tool will provide a spin ephemeris only if the spin ephemeris for the pulsar is valid at the reference time. Thus **gtephem** can be used to ensure that the pulsar ephemerides file includes valid data for a pulsar. Note that if the tool is **not** run with 'strict=yes' on the command line (the default is 'strict=no') then the tool will extrapolate the spin ephemeris beyond the valid time range. Orbital ephemerides are considered to be always valid.

Running **gtephem** with 'chatter=4' on the command line provides not only the spin ephemeris at the reference time, but the spin and orbit ephemerides in the database file. Thus using this option you can query the database.

9.6.2 Manipulating Pulsar Ephemerides Files

The *Fermi* tool **gtpulsardb** creates a new pulsar ephemerides file by extracting ephemerides from one or more pulsar ephemerides files; see the Ephemeris Data File analysis thread for examples.

The ephemeris for a specific pulsar can be extracted from the input pulsar ephemerides file and written out to the output pulsar ephemerides file by entering 'NAME' at the 'Filter ephemerides' query and then entering the pulsar name. Note that the input file may have multiple names for a given pulsar but a name must be entered exactly as spelled in the input file.

The ephemerides for all pulsars that have valid time ranges during some portion of a user-specified time range are extracted by entering 'TIME' at the 'Filter ephemerides' and then providing the time range. Note that the valid and user-specified time ranges must only overlap for the pulsar ephemeris to be extracted; one need not be a subset of the other.

As for most FTOOLS, when queried for an input file you may enter the name of an ASCII file with a list of input FITS files. Thus instead of entering the name of a specific FITS-format pulsar ephemerides file, you may enter '@xxxx' where 'xxxx' is the name of an ASCII file with the names of the FITS-format pulsar ephemerides file, each on a separate line. The **gtpulsardb** tool creates a pulsar ephemerides file with ephemerides of all pulsars in all the pulsar ephemerides files that meet the filtering condition; no filtering is an option. Thus **gtpulsardb** can concatenate a group of pulsar ephemerides file into a single file, with and without any filtering.

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10 Observation Simulation

10.1 LAT Simulation Overview

The ultimate goal of a simulation is a realization of the data given a hypothesized model of the sky and the best understanding of the detector. Since the simulation creates one of many possible realizations, re-running the simulation will result in a different realization if the generation of randomness has been altered (e.g., by using a different seed for the random number generator).

Observation simulation is part of parameter fitting, which was discussed in the likelihood section. There a physical model of the sky is folded through the detector response to calculate the expected count model. This count model is a probability distribution function that is a continuous function of the observables such as apparent energy and apparent position on the sky. In fitting this distribution function is used to calculate the likelihood value for the observed counts. Here, the distribution function is used to create a realization of the data, i.e., integral counts at specific values of the observables.

In the case of the LAT, we need to provide models of where the LAT was pointing and the gamma-ray emissions of sources within the LAT's field-of-view (FOV) over the period of the simulated observation. As was discussed in the section on LAT data products, the time history of the LAT pointing is provided by the 'spacecraft file' (also known as an FT2 file). An existing spacecraft file may suffice for your simulation since you may be interested in a simulating the data for a specific observation that has already occurred (and therefore the actual spacecraft file can be used) or for an average survey observation (in which case an spacecraft file of the correct duration can be used if *Fermi* was in survey mode). However, you might want design an observation, in which case you need to model *Fermi*'s orbit and the LAT's pointing relative to this orbit; this is done with the **gtorbsim** tool, as discussed in the next section. The model of the sky is provided through an XML file that can be created and edited by the ModelEditor tool, which is discussed in a subsequent section. This model includes information about the source, such as: integral flux, spectral model (e.g., power law), spectral parameters (e.g., photon spectral index for a power law model), energy range, and source position (e.g., RA, DEC).

The **gtobssim** tool then uses the spacecraft and model files to create an event file (.FT1) that can be analyzed with the same tools that can be applied to real data. For a given LAT pointing history and sky model there is an expected gamma-ray flux incident on the LAT. **gtobssim** samples this expected gamma-ray flux to create a photon list. The analytic response functions are then applied to map this photon list into a observed count list: the effective area provides the probability that the photon is detected, and the apparent origin and energy of the detected photon is calculated from the point-spread function and energy redistribution function, respectively. Because the creation of the photon list and the mapping of the photon's parameters onto the detected count's observables are probabilistic processes, the code uses a random number generator, and **gtobssim** runs with different seeds will produce different count lists.

gtobssim uses XML model files to generate source photons with appropriate directions. These models are generally characterized by many more parameters than the actual data will justify statistically, and therefore the data will generally be fit by **gtlike** using simpler models. For historical reasons the **gtobssim** XML model files and the **gtlike** XML model files have different syntax.

The event file produced by **gtobssim** is the same filetype as the event files that will result from LAT observations, and therefore can be analyzed in the same way. Thus you can explore the data and fit models with the same tools that you will use to study real data.

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10.2 Orbit Simulation

In most cases, an existing spacecraft file or a simple rocking strategy (implemented by default in the **gtobssim** tool) will meet the simulation needs of Guest Investigators. If this is true, you may skip this section and proceed to Observation Simulation.

If an existing spacecraft file will not suffice for the observation that you wish to simulate then you can create your own spacecraft file. The *Fermi* orbit simulator tool **gtorbsim** is a spacecraft attitude calculator based on the code already implemented in the general purpose *Fermi* scheduling and planning system TAKO (Timeline Assembler Keyword Oriented). The **gtorbsim** simulator inherits many features of TAKO, but it does not have any scheduling capabilities. The main purpose of this simulator is:

- To calculate spacecraft attitude, that is where the local body frame axes are oriented relative to the sky
- To determine when events such as entry/exit in South Atlantic Anomaly (SAA) will take place

10.2.1.1 Observing Modes

gtorbsim allows you to simulate two types of scientific observation modes: survey and pointed.

- The sky survey mode is basically zenith pointed throughout the orbit and has two sub modes: 1) with rocking, and 2) without rocking. Rocking provides for more uniform sky coverage and allows for complete sky coverage within a shorter period of time. Different rocking profiles may be implemented (square or sinusoid), with a basic 2-orbit period and a 60-degree maximum amplitude (above and below the orbit plane).

  In survey mode you may chose between two options: fixed or profiled.

  - In fixed survey mode the spacecraft does a sky survey with a specified offset with respect to its local zenith for one orbit, and then uses the opposite offset for the next orbit, and so on. The current default is a 2-orbit period square profile with a 35 degree rocking angle.
  - In profiled survey the spacecraft observes in survey mode according to a specified profile consisting of 17 increasing times and 17 zenith offsets. The 17 increasing times (in seconds) are used to indicate during each cycle the time that it takes to go from a corresponding zenith offset to the next. The 17 angles (in degrees) are the zenith offsets reached at the end of the corresponding time where the first and last must be identical in order than the profile could be repeated.

- In pointed observation mode, the Z-axis of the observatory is pointed to a commanded celestial target. An observing sequence is implemented via a series of commanded targets. Each target is maintained in the LAT FoV by commanding the observatory in target inertial mode, which keeps the Z-axis on the target to within the 2 degrees control capability of the spacecraft.

  Pointed observation mode may be interrupted for downlink transmissions of science data. Earth avoidance is accomplished in this mode via stored commands that keep the field of view on the sky while the target is occulted. Alternatively, an automatic earth avoidance capability may be used.

Even though it is possible to do pointed observations, the large FOV of the LAT provides such extensive data on individual sources that it will be difficult to justify others types of observation modes than sky survey. For that reason, it is expected that *Fermi* will operate in sky-survey mode ~90% of the time. You may be using the *Fermi* simulation tools to attempt to justify a pointed observation rather than relying on the survey mode data.

10.2.1.2 Spacecraft Position

gtorbsim needs to know the spacecraft position in the entire interval of interest in order to properly calculate the attitude, therefore it must be capable of either reading in a file that contains the spacecraft ephemeris, or to calculate one on the fly. **gtorbsim** can handle three different types of ephemeris files:

- NASA Flight Dynamic Facility (FDF) format, already used for missions such as RXTE.
- Satellite Tool Kit (STK) format, already in use for SWIFT.
- NORAD Two Line Elements (see http://celestrak.com/NORAD/elements), in which case the spacecraft position is calculated by **gtorbsim** on the fly. This will be the easiest ephemeris to obtain, and is sufficient for simulations of 30 days or less.

Additionally, the initial spacecraft position should be provided as parameter of the tool in celestial coordinates.

10.2.1.3 South Atlantic Anomaly Passages

The instrument high voltage power supplies will be protected when the spacecraft traverses the South Atlantic Anomaly (SAA); *Fermi* will be in the SAA ~15% of the time. **gtorbsim** models the SAA passages. The SAA region is identified by a polygon specified by the longitude and latitude of its vertices, which are passed to the program through an input file. When this file is not available, a default hard-coded table of longitude and latitude pairs of vertices will be used. In addition to an ephemeris point being in the SAA polynomial, the ephemeris point prior will also be included as in the SAA region, since somewhere between the two points is when the actual SAA is encountered.

10.2.1.4 Earth Limb Avoidance

If enabled, *Fermi's* flight software will keep the Earth's limb out of the LAT's field-of-view by tracing the Earth's limb; this is modeled by **gtorbsim**. In general, this maneuver will not be necessary because the observing timeline will be constructed to point the LAT at a secondary target when the primary target will be occulted by the Earth. Nonetheless, when a secondary target has not been planned into the observing timeline, **gtorbsim** calculates the occultation times, and then performs the Earth Limb tracing maneuvering. The occultation times are calculated using the same algorithm used by TAKO.

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10.3 Observation Simulation

Once you have obtained the spacecraft and model files appropriate for the observation you wish to simulate, as described in previous sections, you can run the **gtobssim** tool to perform the simulation. In addition to inputting these two files, you will input the simulation start time and duration.

The methodology behind **gtobssim** is probabilistic and uses a random number generator. Therefore you will enter the random number seed. You can recreate the exact same realization by entering the same seed, and create a series of realizations by running **gtobssim** with different seeds.

Different event classes can be used for different types of analysis; each class has its own set of response functions. Since **gtobssim** uses response functions to create the simulations, you must specify the set of response functions for a run.

The source model file may contain more sources than you want to simulate for a given task. You will need to provide an ASCII file with the list of source you are interested to simulate for that specific simulation as an input of **gtobssim**.

Note that not all sources available in **gtobssim** are available in **gtlike**. You may want to use **gtlike** to perform a likelihood analysis on your simulated data set in order to obtain the significance of a detection. The source models that are included in **gtlike** are a subset of the ones available in **gtobssim**. You should keep this fact in mind in pursuing your analysis.

For a number of simulation examples, please refer to the analysis threads.

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10.4 Model Creation

The model of the sky used by **gtobssim** is stored as an XML file. The format of this XML file differs from that used by **gtlike**. All the source models used by **gtlike** can be expressed as **gtobssim** source models, but the **gtobssim** XML format does not include parameter uncertainties. In the next section we provide a simple example of XML for a point source.

Although the **gtobssim** XML format differs from the **gtlike** XML format, the same Model Editor tool (see the likelihood section) can create and edit the files from both formats. This tool can also convert between formats, within the capabilities of these formats. Thus the parameter uncertainties in a **gtlike** XML model will be lost in creating a **gtobssim** XML file, and conversely, the time dependence of a **gtobssim** XML file will not carry over to the **gtlike** model. Use of this GUI-driven tool is fairly intuitive.

Note that you can create a model with more sources than you intend to use in **gtobssim** simulation.

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10.5 Simple Models

XML is not meant for human eyes. Software is supposed to read and write these files, insulating the human from all the '<' and '>' symbols. However, an example of the XML file for a simple point source might assist you in understanding the XML model files that are used for simulations. And if you want to change one parameter in a model file, you might venture where no human is meant to, and edit the XML file directly with an ASCII editor.

The following is the model for a point source:

```
<source_library title="example_3C279">
 <source name="_3C279" flux="3.48e-4">
        <spectrum escale="MeV">
           <particle name="gamma">
              <power_law emin="20.0" emax="200000." gamma="1.96"/>
           </particle>
           <celestial_dir ra="193.98" dec="-5.82"/>
        </spectrum>
 </source>
</source_library>
```

Clearly, the point source is supposed to model 3C279 and is located at (Ra=193.98, Dec=-5.82). The spectrum is a power law with a photon spectral index of 1.96 and an integrated flux of 3.48e-4 $m^{-2}s^{-1}$ over 20 to 20,000 MeV. Note that all the spectral parameters are in one tag. Because this XML format is also used within the *Fermi* mission to model non-photon fluxes impinging on the LAT, the particle type is given as 'photon' (which will always be the case for simulating astrophysical sources)

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10.6 Simulating GBM Data

Through its 'fakeit' command the **xspec** spectral analysis tool is capable of simulating model count spectra given a background spectrum and a response matrix. The simulated model can then be fit by **xspec** as though it were a real spectrum. The simulated count spectrum, plots and other products can be stored in standard file formats.

To use 'fakeit' you must first load in a background file in the standard PHA format and the response matrix in the standard RSP format. Background and response files are provided with every GBM burst. Instructions in the use of 'fakeit' can be found in the **xspec** manual.

This simulation capability was behind the 'Fermispec' (formerly GLASTspec) webtool.

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11 GLOSSARY

Terms used in a definition that have there own glossary entry are italicized.

Term or Acronym	Definition
ACD	*Anti-Coincidence Detector*
Anti-Coincidence Detector (ACD)	Scintillating tiles on the surface of the LAT that veto events resulting from charged particles form outside the LAT.
BATSE	*Burst And Transient Source Experiment*—the gamma-ray burst detector on *CGRO.*
CAL	*Calorimeter*
Calorimeter (CAL)	Set of CsI logs at the bottom of the LAT that track, stop and record the energy of the electron-positron pair resulting from gamma rays that pair produce in the *Tracker.*
CGRO	*Compton Gamma Ray Observatory*—gamma-ray mission that operated between 1991 and 2000.
Effective Area	The number of photons detected divided by the source flux. The LAT effective area is a function of photon energy and *inclination angle.*
Event File	FITS file with LAT events. Uses the .FT1 extension.
Field-of-View (FOV)	Size of the region of the sky from which a detector accumulates data. The FOV has two definitions. One is the integral of the effective area over the sky divided by the on-axis effective area. The second is the total area of the sky over which useful data can be accumulated, even if the effective area is much less than the maximum.
FITS File	File with a standard, self-defining structure. FITS files consist of one or more *HDUs*, an ASCII header and a data table. The header contains keywords identifying the file and *HDU,* or defining the data. The first HDU is used for images, and often does not include any data. FITS stands for 'Flexible Image Transport System.'
FOT	Flight Operations Team—the staff at the *MOC* during the mission.
FTOOLS	A package of tools to manipulate *FITS files.*
FOV	*Field-of-View*
GCN	Gamma-Ray Coordinates Network—system that receives and disseminates burst information.
HDU	Basic unit of a *FITS file* consisting of an ASCII header and a data table. HDU stands for 'header and data unit.'
Inclination Angle	The angle between the direction to a source and the LAT detector

	normal.
Instrument Response Function (IRF)	Mapping between the quantities describing an incident photon (e.g., energy, direction) and the observables reported by an instrument.
IRF	*Instrument Response Function*
LAT	Large Area Telescope
Likelihood	Probably of obtaining the data given a model.
Livetime Cube	Array of the livetimes at a given LAT *inclination angle* at grid points over the entire sky. The livetime cube is stored in a FITS file.
MET	*Mission Elapsed Time*
Mission Elapsed Time (MET)	The number of seconds since midnight January 1, 2001 (UTC). MET is the time system used by all science software and data products.
MOC	Mission Operations Center—the organization that controls the spacecraft. The MOC is housed at GSFC.
Photo-Multiplier Tube (PMT)	A vacuum tube that emits a large electron current proportional to the small number of photons that enter the tube.
PMT	*Photo-Multiplier Tube*
Point Spread Function (PSF)	The distribution of the angular distance between a photon's actual and apparent positions. The LAT PSF is a function of photon energy and *inclination angle.*
PSF	*Point Spread Function*
Region of Interest (ROI)	Spatial region from which LAT photons are accumulated.
ROI	*Region of Interest*
SAA	*South Atlantic Anomaly*
SAE	Standard Analysis Environment—the *Fermi*-specific data analysis tools. Also known as the *Fermi* Science Tools.
Source Region	Spatial region whose gamma-ray sources are included in an analysis of LAT data. The Source Region should be larger than the *Region of Interest*.
South Atlantic Anomaly (SAA)	Region over the south Atlantic where the trapped radiation is very large, requiring detectors to be turned off.
Spacecraft File	FITS file with the time history of the spacecraft position, LAT orientation and LAT livetime. Uses the .FT2 extension.
Target of Opportunity (TOO)	A target that is observed on a short timescale resulting from a change in the target (e.g., a flare).
TDRSS	*Tracking and Data Relay Satellite System*
Test Statistic (TS)	Statistic used to compare a model with a source to the model without

	the source (the null hypothesis). The TS is equal to -2 times the logarithm of the ratio of the *likelihoods* for the model with and without the source.
TKR	*Tracker*
TOO	*Target of Opportunity*
Tracking and Data Relay Satellite System (TDRSS)	Constellation of geosynchronous satellites through which NASA spacecraft can send and receive data. An individual satellite is called a Tracking and Data Relay Satellite (TDRS).
Tracker (TKR)	Component of the LAT consisting of tungsten foils in which gamma rays pair produce and *Silicon Strip Detectors* that track the passage of the resulting electron-positron pairs.
TS	*Test Statistic*
Zenith	Point on the sky opposite the earth.

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